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An Investigation of

Hooped Concrete Columns

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AN INVESTIGATION OF HOOPED CONCRETE COLUMNS

BY

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY JULIAN MONTGOMERY

ENTITLED AN INVESTIGATION OF HOOPED CONCRETE COLUMNS.

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN THEORETICAL AND APPLIED MECHANICS.

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on
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I. INTRODUCTION

1. Preliminary.- In the year 1914, an elaborate series of tests of spirally reinforced concrete columns was made as thesis work at the University of Illinois Engineering Experiment Station. During the same year the staff of that station supervised the testing of similarly constructed columns at Pittsburg, Pa. While the results of these tests cleared up some mooted points regarding hoop action, a careful study of the two series of tests showed the need for further investigation. The fact was also revealed that much of the labor of former tests could be eliminated, as many of the gage lines formerly placed on the columns were found to be unnecessary. It was demonstrated, further, that only a certain portion of the column need be investigated where the result desired was the hooping action.

Because broken stone was used for the concrete columns tested at the Experiment Station, and gravel for those tested at Pittsburg, the two series of tests do not permit of direct comparison. In choosing the variables to be studied in this thesis, it was decided, among other things, that a comparison of the two aggregates in a series of tests was desirable. Also, it was thought that the light thrown on hoop action by a series of tests containing the variables that the former results had not eliminated, would do much to augment definite conclusions on the subject. It was with this end in view that the tests contained in this thesis were planned.

2. Scope.- The series of tests herein contained were devised to show the results of spiral action due to the variation of the amount of spiral reinforcement, the amount of cement, and the

kind of aggregate. Thirty-three spirally reinforced concrete columns and twelve plain concrete columns composed the series. Each mixture, with the exception of the I-3-6, contained three different percentages of spiral, with three columns for each percentage. This made nine reinforced columns for each mix (six for the I-3-6), resulting in thirty-three columns altogether. In addition to these, there were three plain columns of each mix, a total of twelve. Mention should be made of the fact that there were two mixes of I-2-4 concrete; one of broken limestone and the other of gravel.

Besides comparing the broken stone with the gravel concrete, the results contained in this thesis contrast the moduli of elasticity, maximum strengths, added loads, Poisson's ratios, yield points, deformations, total lateral pressures, and economic considerations of the columns containing varying amounts of spiral for the different mixes.

3. Acknowledgment.- The writer is indebted to Professor Arthur N. Talbot, Professor in charge of Theoretical and Applied Mechanics, for his general supervision, advice, and suggestions relative to this thesis. To Mr. H. F. Gonnerman, First Assistant in the Experiment Station, who had direct charge of fabrication and testing during the enforced absence of the writer, and who aided also in the review of this thesis, the writer wishes to express a sincere appreciation, not only for the creditable assistance rendered, but for the willingness and sympathetic cooperation shown at all times. Mr. H. R. Thomas, M. S. University of Illinois 1914, who submitted a thesis on this same subject, has furnished

much valuable aid in the reduction of data, drawing of diagrams, and interpretation of results. Acknowledgment is also made to Mr. J. O. Draffin, Research Fellow in the Experiment Station, who aided in the testing.

4. Theories of Hoop Action.- Turneaure and Maurer's "Principles of Reinforced Concrete" 1911 edition, page 131, gives a derivation of a hooped column formula considering the steel as a thin cylinder and the concrete as an elastic material. Some incorrect assumptions are made in this derivation. The result is that an incorrect formula is obtained.

The following derivation, submitted by the writer, closely follows the first part given by Turneaure and Maurer. However, some notations and assumptions based on fundamental laws governing elastic, homogeneous materials are contained in it which would seem to make the derivation more appropriate than the one given by Turneaure and Maurer.

Let u = Poisson's ratio for concrete.

P = Steel ratio considered as thin cylinder.

A_s = Cross section of this thin cylinder.

t = Thickness of assumed cylinder.

r = Radius of the column.

f'_c = Vertical unit load on the column.

ϵ' = vertical unit deformation caused by f'_c on unrestrained column.

ϵ = net vertical unit deformation in the restrained column when it carries unit load f'_c.

f_c = vertical unit load that would cause a deformation of ϵ in unrestrained column. = ϵE_c.

f_s = unit stress in the steel.

E_s = modulus of elasticity of the steel.

E_c = modulus of elasticity of the concrete.

$n = E_s / E_c$.

Now $A_s = P\pi r^2$ and $t = \frac{P\pi r^2}{2\pi r} = \frac{Pr}{2}$.

Also $2 f_s t = f_s Pr$ = total stress in steel per in. of length of cylinder. This steel stress exerts a pressure on the concrete. If we call the unit pressure thus caused $\underline{V}$, then

$$2rV = f_s Pr$$

$$V = \frac{f_s P}{2}$$

As the lateral pressure on the concrete exerted by the steel is in effect on two faces at right angles, the resultant lateral deformation due to the pressure caused by the steel restraint is-

$$\frac{f_s P}{2 E_c} (I-u)$$

Had there been no restraint, the swelling caused by the vertical load f_c' would have been--

$$u\epsilon' .$$

As the lateral deformation caused by the vertical load is opposite to that caused by the pressure due to the steel, the resultant lateral deformation is -

$$u\epsilon' - \frac{f_s P}{2E_c} (I- u)$$

This is the lateral deformation and is equal to the deformation in the steel, $\frac{f_s}{E_s} = \frac{f_s}{nE_c}$.

Therefore $u\epsilon' - \frac{f_s P}{2E_c}(I-u) = \frac{f_s}{nE_c}$

or $$u\epsilon' E_c - \frac{f_s P}{2}(I-u) = \frac{f_s}{n} \quad \text{------------ I.}$$

Now the effect of the lateral pressure on the concrete, in the two lateral directions, is to cause an upward vertical deformation of $2u\frac{f_s P}{2E_c}$

Hence $\epsilon = \epsilon' - u\frac{f_s P}{E_c}$ or $f_s = \frac{\epsilon' E_c - \epsilon E_c}{u\,P}$ --------2.

From(I) we get $f_s = \frac{u\epsilon' E_c}{\left[\frac{I}{n} + \frac{P}{2}(I-u)\right]}$

Substituting in this the value of f_s given by(2) we have

$$\frac{\epsilon' E_c - \epsilon E_c}{uP} = \frac{u\epsilon' E_c}{\left[\frac{I}{n} + \frac{P}{2}(I-u)\right]}$$

From definition $\epsilon E_c = f_c$ and $\epsilon' E_c = f'_c$. Substituting their values

$$\frac{f'_c - f_c}{uP} = \frac{u\,f'_c}{\left[\frac{I}{n} + \frac{P}{2}(I-u)\right]}$$

$$f'_c = f_c\left(I + \frac{u^2 P}{\left[\frac{I}{n} + \frac{P}{2}(I-u) - \mu^2 P\right]}\right)$$

If it be assumed that the deteriorating effect of compression loading is measured by the longitudional deformation produced in concrete, either restrained or not restrained(a corallary of The Maximum Strain Theory), then the value of f_c which will produce an amount of longitudional deformation equal to that which the unrestrained concrete would have at failure(i.e. the ultimate compression strength of plain concrete), may be used for f_c and the above formula for f'_c will give the stress which will cause the same condition of internal strain as exists in plain concrete at failure.

Considere has made extensive theoretical and experimental investigations of hooped columns, fro which he concluded that the concrete acts similarly to a granular material after the spiral begins to take stress. In the absence of reliable data on the coefficient of internal friction of concrete, he took the coefficient of friction of sand and applied it to concrete. The expression he obtained for the ultimate strength of the column is given by the formula

$$P/A = f_c + 2.4pf_s$$

where f_c is the strength of the concrete and f_s is the elastic limit of the steel.

II. MATERIALS, TEST PIECES and METHODS of TESTING.

1. Concrete Materials.— The materials used for the concrete were similar to those ordinarily found in the open market.

Stone. The stone was crushed limestone from Kankakee, Ill. That used for the columns was passed thru a 1-in. screen and over a 1/4 in. screen. The stone was somewhat soft in quality, and averaged 89 lb. per cu.ft. in weight (wet). It contained from 45 to 50 percent. voids. Table I gives the mechanical analyses of 3 samples of this stone.

TABLE I

Mechanical Analysis of Stone.

Each value is the average of three tests

Size of Sq. Opening.	Separation Size – in.	Percent Passing Sieve.
1 in.	...	99.7
3/4 in.	...	97.0
1/2 in.	...	76.2
3/8 in/	...	53.5
No. 3	0.280	32.6
No. 5	.174	6.5
No. 10	.091	3.6

Gravel. The gravel was obtained from the open market. In general the pebbles were smooth and round, rather than long and sharp or flat. It was clean and of a harder quality than the limestone. The average weight per cu.ft. was 98.5 lb. Table II gives the mechanical analysis of four samples of this stone.

Sand. The sand came from near Attica Indiana. It was very well graded asshown by fineness tests of 5 samples given in Table III.

Cement. The specimens were made with Universal portland cement. Table IV gives the results of briquette tests of the cement. These results seem to indicate that the strength of the cement was not up to that of former years.

TABLE II.

Mechanical Analysis of Gravel.

Each value is the average of four tests.

Size of Sq. Opening.	Separation Size. – in.	Percent Passing Sieve.
1 in.	...	87.7
3/4 "	...	71.2
1/2 "	...	27.4
3/8 "	...	9.7
No. 3	0.280	3.9
No. 5	.174	0.8
No. 10	.091	0.5

TABLE III.

Mechanical Analysis of Sand.

Each value is the averago of five tests

Sieve No.	Separation Size – in.	Percent. Passing Sieve.		
3	0.280	99.9		
5	.174	89.1	90	4
10	.091	60.7	61	8
12	.067	53.6		
16.	—	46.9		
18	.043	38.1	40	16
30	.027	24.4	18	30
40	.019	11.1		
50	.013	4.6	4	
74	.009	2.7		
150	...	0.9	1	100

TABLE IV.

Briquette Tests of Cement

Each value is the average of five tests.
Standard Ottawa Sand was used for the 1–3 briquettes.

No.	Neat 7 da.	Neat 28 da.	1–3 Mortar. 7 da.	1–3 Mortar. 28 da.
1	514	653	187	304
2	506	665	167	276
Av.	510	659	177	290

These results are expressed in lb. per sq. in.

<u>Steel</u> <u>Tension</u> <u>Test</u> <u>Pieces</u>. Two eight-foot test pieces of each size of the spiral wire were furnished by the manufacturers of the spirals, The Concrete-Steel Products Co. of Chicago. These pieces were cut into two-foot lengths, giving eight tension test pieces for each size of spiral wire. Six of these eight were tested. From the experience gained in former tests, it was thought advisable to save the two remaining pieces for later tests should the need for more data arise. The 1/4 in. and the 5/16 in. coupons were tested in a 10 000 lb. Olsen wire-testing machine; the 1/2 in. in a 50 000 lb. Riehle. An Ewing extensometer was used to obtain deformations up to .023 in. , which corresponded to a unit stress of between 50 000 and 60 000 lb. per sq. in. Loads were read for given increments of deformation. When the steel had reached the deformation of .023 in. in 8 inches, the Ewing extensometer was removed and the deformations up to the ultimate load were read on an eight inch vernier, which was accurate to .01 in. This vernier was attached to the specimen at the beginning of the test. Elongation in 8-in., reduction in area, and maximum loads were also obtained. The data for the six specimens of the same size of wire were averaged and the average curve plotted.

Using Johnson's method for determining the yield-point, the yield points given by the average curves are: 50 000 lb. per sq.in. for the 1/4 in. wire; 47 000 lb. per sq. in. for the 5/16 in.; 49 000 lb. per sq. in. for the 1/2 in. The 1/2 in. steel was the most ductile and the 1/4 in. the least. Table V gives the physical properties of the steel.

TABLE V.

Tension Tests of Steel.

Each value given is the average for six tests.

Size Steel Nominal	Act.	Reduct'n. Percent	Elongation in 8 in.	Yield Pt. lb./sq.in.	Max. Load. lb./sq.in.	Mod.of Elas. lb./sq.in.
1/4"	.247	28.0	10.3%	50 000	97 450	26 500 000
5/16	.310	34.3	13.5	47 000	97 700	26 000 000
1/2	.502	45.7	17.5	49 000	92 250	29 000 000

2 Specimens. The columns were designed to be 40 in. in height and 8 in. in diameter center-to-center of the spirals.

Immediately upon arrival, the spirals were measured and inspected as to the condition of the diameter, pitch, spacing bars, etc. Diameters out-to-out of spirals were measured in two directions at the top, center and bottom and also at any other position where there seemed to be a variation. The variation in pitch for 18 inches was measured.

The pitch for the 1/2 in. and the 1/4 in. spirals was 1 1/2 in. That for the 5/16 in. spirals was 1 in. This difference in the spacing for the different sizes was found necessary in order to obtain the desired variation in the amount of spiral. Four spacing bars were utilized for each spiral. Those for the 1/2 in. and for the 1/4 in. spirals were small channel bars either 7/8in.x1/16in.x1/4 in. or 3/4in.x3/32in.x1/4in. The ones for the 5/16 in. spirals were flat bars 3/4in. by 1/8 in. All of the bars were slotted at the proper distance to give the correct pitch to the spirals. On the whole, the flat bars were found to be in a worse condition than the channels. They were more easily bent and warped.

The last four turns at each end of the spiral were securely bound in pairs by wire. These pairs were from 1/2 in. to 1 1/2 in. apart. The ends of the spiral were bent toward the center.

3. Forms.- As the test specimens were to be only 40 in. long, and as previous tests had shown the importance of having straight columns, it was decided to purchase for forms four pieces of steel pipe 8 in. in diameter and 40 in. long.

The pipes were purchased from Crane Co., of Indianapolis, Ind. After their arrival, each one was cut longitudinally into four uniform pieces. In two of the forms places were made to hold steel plugs to be used for gage points. (For details of plug see drawing 4). By doing this the concrete did not have to be disturbed by cutting plug holes with a chisel, a practice which was considered might possibly cause variations in the strength of plain columns of so small a diameter.

The form was assembled around the spiral while it was lying horizontally, and was held in place with steel bands tightened by screws. Usually narrow wooden strips were inserted between the pieces of pipe. This was done to increase the diameter of the form until it would accomodate the spiral reinforcement at the section of greatest diameter. When the form was in place on the spiral the steel bands holding it together were tightened to as snug a fit as possible. The forms then were placed upright on an oiled cast iron plate, ready for the pouring of the concrete.

4. Construction,- Preliminary to pouring the columns, the weight per cubic foot of each of the materials, sand, stone, and gravel, was determined. These weights were used as a basis for proportioning, by loose volume, the mixtures for the columns.

In order to obtain as much information as possible of the probable causes of variation in the ultimate strength of the concrete, it was thought desirable to keep an accurate account of the water entering the mixture. The sand used in the columns was placed near steam pipes about 24 hours previous to using and kept there until time for mixing. This insured perfectly dry sand. The stone was placed in a bottomless box near the mixing place where it was wetted down each day immediately prior to using. A sample of the stone used in each batch of the concrete was taken for determining the amount of water in it. By wetting down the stone beforehand a more uniform distribution of the cement in the batch was assured by reason of its clinging to the wet stone.

The mixing was done by hand with shovels. The concrete floor adjacent to the place where the columns were to be stured made an ideal mixing place. Mr. H. F. Gonnerman supervised the mixing and pouring. One man did all the weighing. Another, usually Mr. Gonnerman himself, or the writer, kept an account of the weights and checked them against the proportioning weights. A record of these weights was kept and this record is embodied in table 7. The dry sand, taken directly from the drying platform, was weighed first. The proper amount of cement was weighed and poured onto the sand. The sand and cement then were mixed thoroughly. This done, the dry mixture of cement and sand was poured onto the previously wetted stone. The whole was then turned twice. The proper amount of water was poured onto the dry batch which usually was turned four times, and in all cases until a uniform plastic mixture resulted.

In arranging the construction schedule, care was taken to make the columns of the same group on separate dates. Then should

anything occur to affect the strength of the columns built on any one day, the remaining columns of the group would prevent this variation in strength from being ascribed to the particular variables entering that group.

A separate batch of concrete was made for each column and its two auxiliary specimens. The forms for the columns and cylinders were set up on thick glass or cast iron plates. The columns were poured first, a shovelful at a time. Each shovelful was thoroughly stirred. The mixture was usually too wet for much tamping, but this stirring seemed to work the concrete well around the spiral and to expel some of the entrained air. The tamper used for stirring was about 3 in. in diameter, 2 inches thick, with a handle some three feet long. During the pouring the batch was kept of a uniform mix by being turned occasionally. The two cylinders were poured after the column. The batch being small, it was possible to keep it thoroly mixed and intact thruout the pouring. The time consumed in building a column was from 30 to 45 minutes. About 1/2 bucketful of concrete was left over from each batch. After the column and cylinders had been made the floor was swept clean in preparation for the next batch.

When the concrete had settled in the forms a cap of neat cement mortar was placed on each specimen. A glass plate was then put on carefully to make a smooth even surface, and left in place until the form was removed.

The schedule called for the pouring of two columns a day, excluding Sundays, and this was adhered to as closely as possible.

It might be well to mention that this is the first series of column tests at the University of Illinois in which pipe forms

were used to insure perfectly straight columns for all specimens.

5. Auxiliary Specimens.- After each column was poured, two 8 in. by 16 in. cylinders were made from the concrete remaining from the batch. In a few instances the cylinders were made when the columns were half poured, but as the batch of concrete was small and was kept well mixed during pouring, it was thought that the concrete in the cylinders would be representative of that in the column whether the cylinders were made after or during the pouring of the column.

6. Storage.At the end of two days the forms were removed from the columns and the columns were then covered with burlap. This was wetted down every day to insure a damp inclosure for the columns. A week before they were to be tested, the columns were taken from under the burlap and allowed to dry out.

The cylinders were removed from the forms at the end of two days and stored in damp sand. Before testing, the cylinders were allowed to dry out in the same manner as their corresponding columns.

As the columns and cylinders were made and stored in the same room, they were subjected practically to no change in temperature during the whole period of storage. The temperature was kept as nearly constant as the circumstances permitted. The variation from 70°F. was not over 10° thruout the period of making and storing.

7. Preparation for Testing.- Altogether 45 columns were tested. 12 were of 1-1-2 broken stone mix, 12 of 1-2-4 stone mix, 9 of 1-3-6 broken stone mix, and 12 of 1-2-4 gravel mix. There were three columns for each different amount of reinforcement, making four groups to each mix,- excluding the 1-3-6 stone mix which

did not contain the largest amount of spiral.

About a week before the columns were to be tested they were brought over to the Testing Laboratory. This gave them several days in which to dry out. An experienced man placed the steel plugs in the columns and prepared the gage holes. Except for the plain columns which had plugs inserted during the making, round plugs 1/2 in. in diameter and 3/4 in. long were inserted 10 in. apart between the spirals for the longitudinal gage lines. Two columns of each group had 12 longitudinal and 12 lateral gage lines. Four four-inch lateral gage lines were placed on the circumference of the spiral at the quarter points at the center of the column; also at sections 12 in. above and below the middle of the column. Details of the location of these gage lines are given by the drawing on page 149. Each lateral gage line was crossed by a 10-in. longitudinal gage line. For the third column of the group, the longitudinal gage lines were 12 in number and located similarly to those of the other two columns. The number of lateral gage lines, however, was increased to 20. This number embraced the 12 gage lines similarly located to those in the other two columns, with an additional row of four gage lines located two inches from the top and bottom of the column, respectively.

8. Testing.— On the day the column was due to be tested it was set up in the 600 000-lb. Riehle testing machine in the Laboratory of Applied Mechanics. If the ends of the columns were not smooth or did not give a good bearing, the cast iron distributing plates were set in plaster of paris. Four men usually were employed in the testing. Two manipulated the extensometers, one recorded and one ran the testing machine and supervised the testing.

Two sets of zero readings were taken with the multiple reading extensometer and one set with the direct reading instrument. The latter was used on the longitudinal gage lines after the longitudinal deformation had become too great for the multiple ratio instrument, which had a possible range of only 1/10 of an inch as against one inch for the direct reading instrument. One observer took readings on all of the lateral gage lines and the other on the longitudinal ones.

For the first few columns, no deflection readings were taken except the deflection from the vertical at the maximum load. This deflection was determined by holding a string tangent to the top and bottom of the column and measuring the distance from the string to the column at the point of bend. Later, a piece of wood of a length slightly less than that of the columns, with steel lugs on the same side near the ends, and with an Ames dial in the center, was used to measure the deflection. This method was found to be unsatisfactory. The length of the wooden deflectometer could not be changed sufficiently, often the column had deformed so much that it could not be inserted between the cast iron distributing plates at the ends of the column. Finally a short stick with an Ames dial on one end and a micrometer screw on the other was used to measure the deflection. Readings were taken in two directions at right angles: from one of the two large screws on opposite sides of the column, and from a vertical piece of flat steel set up parallel to the screws and half way between them. This method was found to be satisfactory.

Before applying the load, measurements were taken of the

length of the column and of the diameters out-to-out of the concrete and out-to-out of the spirals at the top, center, and bottom. A shell of concrete about 0.2 in. thick usually was found outside of the spiral.

Generally after the application of the first load, wedges were placed between the spherical bearing block and the fixed bearing plate on the crosshead of the testing machine. This fixed the direction of application of the load and insured an even bearing against the changes due to bending and local weaknesses. The load was recorded as soon as applied, two minutes later and at the conclusion of the series of observations. Also on many of the tests an additional load reading was taken after one minute. At first each series was determined by an increment of loading. This gave good results. Still better were obtained by determining the series with increments of deformation. After this method had been adopted, equal load increments were used up to a unit deformation of about 0.001 in the steel. After this deformation, serial increments of 0.001 unit deformation in the steel were used.

Observations were taken of loads at first crack, first sign of spalling, general spalling, and any other physical changes in the column that seemed worth recording.

9. Disposal of the Tested Columns.- As soon as the maximum load was reached the machine was stopped, and the length of the column together with its deflection were measured. The load was removed, the recovery in length was noted, and the column was taken from the testing machine. The tested columns were stacked in the Laboratory. They were arranged in their proper order according

to notation and photographed. These views are given on pages 153 to 159.

10. Auxiliary Tests.- The cylinders were brought over with the columns and the ends set in plaster of paris a day or two before they were due to be tested. At least one of the pair of cylinders was tested before the column so that an idea of the crushing strength of the concrete could be obtained. Extensometer readings were taken on only one of the cylinders. The data obtained from the previously tested cylinders were a great help in determining the load increments for the columns.

Table 7 gives the maximum loads, moduli of elasticity, and age at date of test for the cylinders.

III. EXPERIMENTAL DATA AND DISCUSSION.

1. Phenomena of Tests.- The following is a recapitulation of the observed phenomena of construction and testing of the columns, with a brief description of spirals and spacing bars whose condition possibly might have a bearing on the results.

8971.1

Scaling first observed at 245 000 lb. Max.load 265 800 lb. Column did not bend at the maximum load. After the maximum load was reached, the load fell off steadily to 250 000 lb. High speed was put on and spirals broke at 235 000 lb. Column did not bend but bulged noticeably just before failure. Column shortened 3/8 in. at 260 000 lb.

8971.2

First vertical crack observed near the top at 210 000 lb. load. Spalling at 270 000 lb. Maximum load 285 000 lb. Column shortened one fourth inch.

8971.3

First vertical crack observed at 222 000 lb. load. Spalling began at 270 000 lb. Maximum load 286 000 lb. Column shortened 1/4 in, at 254 500 lb.

8972.1

All spacing bars were warped, one being bent at a point 18 in. from the bottom. Fine vertical crack observed at 259 000 lb. Spalling began at 289 000 lb. At 391 000 lb. the column apparently began to bend to the East at a point about 12 in. from the top. Maximum load 393 000 lb. Column shortened 1 3/4 in. at maximum.

8972.2

First vertical crack observed near the top at 201 000lb. load. Spalling began at 222 000 lb. No apparent bending at 362 500 lb. Some crushing of the concrete between spirals at 381 000 lb. Gradual bending toward north at the maximum load of 397 000 lb. Column shortened 1 1/4 in. at the maximum.

8972.3

Spacing bars slightly bent. Spiral bent 1/2 in. from vertical 12 in. from the bottom.

First vertical crack came at about 200 000 lb. Concrete crushing between spirals at 350 000 lb. Top began to bend to the east at 360 000 lb. load. Considerable bending at load of 365 400 lb. Column shortened 1 1/4 in. at the maximum load of 366 700 lb.

8973.1

First vertical crack appeared at 258 000 lb. load. Spalling began at 270 000 lb. Maximum load 431 500 lb. Column shortened 1 in. at the maximum load. Deflection at center of column at 429 000 lb. load as load was falling off was about 1/2 in. toward the northwest.

8973.2

First vertical crack appeared in the upper third of the column at 177 000 lb. load. Spalling in large pieces at 276 000 lb. At 401 000 lb. concrete was crushing between spirals. Bending to east noted at 440 000 lb. load. Column shortened 1 3/8 in. at the maximum load of 455 500 lb.

8973.3

First vertical crack observed at 240 000 lb. load. Spalling in upper half began at 270 000 lb. Concrete crushed between spirals 15 in. from the top at 417 000 lb. load. Bending to the south noticed at 442 000 lb. Column shortened 1 1/2 in. at the maximum load of 459 600 lb.

8974.1

Cracking and spalling first observed at 119 000 lb. load. Column shortened 1 1/2 in. at the maximum load of 189 800 lb.

8974.2

First crack observed and a slight spalling noted at 114 500 lb. load. Bending to west began at 202 000 lb. Column shortened 1 3/4 in. at the maximum load of 204 000 lb.

8974.3

Cracking and slight spalling first noted at 110 000 lb. load. Column shortened 1 5/8 in. at the maximum load of 188 500 lb.

8975.1

Three spacing bars slightly bent. Spiral 1 in. out of the vertical at the center.

First vertical crack observed at 116 000 lb. load. Considerable spalling noted at 131 000 lb. Indications of bending to the southeast at 315 000 lb. Pronounced bending at 334 500 lb. Column shortened 2 in. at the maximum load of 334 500 lb.

8975.2

Spacing bars badly warped. Spiral bent in one direction 12 in. from the top and in the opposite direction about the same distance

from the bottom.

First vertical cracks observed at 109 000 lb. load. Spalling began at 127 000 lb. Crushing of the concrete between spirals and a slight bending toward the east noted at 295 000 lb. Column shortened 2 1/4 in. at the maximum load of 319 000 lb.

8975.3

Spacing bars warped and slightly bent. Spiral 3/4 in. off of vertical at 12 in. from the bottom.

A number of fine cracks observed at 133 000 lb. load. Spalling began at 163 000 lb. Apparent bending toward south noted at 307 000 lb. Column shortened 2 in. at the maximum load of 325 700 lb.

8976.1

General cracking and spalling began at 128 000 lb. load. Column bending slightly toward south at 270 000 lb. Severe crushing of the concrete noted at 326 000 lb. Maximum load 340 500 lb.

8976.2

Cracking and spalling noted at 139 000 lb. load. Column began to bend toward the south at 290 000 lb. Column shortened 2½in. at the maximum load of 330 000 lb. Deflection at the center of 2 in. at the maximum load.

8976.3

First vertical cracks observed at 124 000 lb. load. Spalling began at 133 000 lb. Slight crushing of the concrete between the spirals noted at 307 000 lb. Column bending to east at 317 000 lb. Column shortened 2 1/4 in. at the maximum load of 382 000 lb. Concrete appeared not completely dried out.

8977.1

First crack observed at 63 000 lb. load. Spalling began at 85, 000 lb. Column appeared straight at 171 000 lb. Column shortened 2 3/8 in. at the maximum loadof 172 000 lb.

8977.2

First vertical crack observed at 62 000 lb. load. Slight spalling at 81 000 lb. apparent bending to the west at 138 000 lb. Column shortened 1 7/8 in. at the maximum load of 153 600 lb. Concrete appeared not entirely dry.

8977.3

First vertical crack observed at about 60 000 lb. load. Spalling began at 85 500 lb. Column bending to the west at the maximum load. Column shortened 2 1/8 in. at the maximum load of 168 000lb.

8978.1

Spacing bars slightly bent and warped at the bottom. Spiral one inch off of the vertical at the center.

First crack observed at about 80 000 lb. load. Spalling began at 86 000 lb. Bending toward west noticeable at 275 000 lb. Bending to west was accentuated at 284 000 lb. at a point about 12 in. from the top. Column shortened 3 1/4 in. at the maximum load of 319 500 lb.

8978.2

Spacing bars badly bent and warped. Spiral 1/2 in. off of vertical 6 in. from the top. The badly warped spacing bars gave a greater inclination to the individual diameters.

First crack observed at 66 000 lb. load. Bending to the north

noticed at 216 000 lb. Deflection of 5/8 in. at the center at the maximum load. Column shortened 2 3/4 in. at the maximum load of 291 000 lb.

8978.3

Spacing bars warped and bent. Spiral 3/4 in. off of vertical at the center.

First vertical crack observed at 78 000 lb. load . Spalling began at 103 000 lb. Apparent bending to the north and east at 244 500 lb. Column shortened 3 1/4 in. at the maximum load of 299 000 lb.

8979.1

Fine cracks observed near the center of the column at 140 000 lb. load. Spalling began at 163 000 lb. Column apparently bending to the east at the maximum load of 221 000 lb.

8979.2

Spalling noticed at 171 000 lb. load. Column failed by bending to the north-west. Column shortened one inch at the maximum load of 213 000 lb.

8979.3

One spacing bar slightly warped at the top. Gravel seemed slightly dirty.

First crack observed at 163 000 lb. load. Spalling general at 185 000 lb. Crushing of concrete between spirals about 9 in. from the bottom noticed at 210 400 lb. Apparent bending to west at 212 600 lb. Column shortened one inch at the maximum load of 214 000 lb.

8980.1

All spacing bars bent at the bottom.

Cracking and spalling observed at 156 000 lb. load. Bending to east about 12 in. from the top noticed at 332 000 lb. Column shortened 1 3/4 in. at the maximum load of 372 600 lb. Spiral broke through the gage hole of gage line 20 at the maximum load.

8980.2

Spacing bars slightly bent.

First crack observed at 203 000 lb. load. Spalling began at 215 000 lb. Crushing of concrete between spirals 12 in. from the bottom was noticeable at 355 000 lb. Apparent bending to the south at 360 000 lb. Column shortened 2 in. at the maximum load of 397 500 lb.

8980.3

Spacing bars bent and warped at the bottom. Spiral one inch off of vertical 12 in. from the bottom.

First vertical crack observed at 156 000 lb. load. Spalling began at 204 000 lb. Crushing of concrete between spirals 12 in. from the top observed at 346 000 lb. Column began to bend to south about 12 in. from the top at 366 000 lb. Column shortened 1 3/4 in. at the maximum load of 383 000lb.

8981.1

Concrete should have been mixed wetter.

First crack appeared at 164 000 lb. load. Spalling began at about 180 000 lb. Slight bending to east noticed at 399 000 lb. Maximum load 424 500 lb.

8981.2

First vertical cracks observed in the upper third of the column at 155 000 lb. load. Spalling began at 180 000 lb. Crushing of the concrete between spirals was noticed at 392 000 lb. Apparent bending to the west at 435 000 lb. Column shortened 2 in. at the maximum load of 464 700 lb.

8981.3

Fine vertical cracks observed at 159 000 lb. load. Spalling began at 196 000 lb. Crushing of the concrete between spirals noticed at 368 000 lb. Considerable bending to the north at 448 000 lb. Deflection of 3/4 in. at the center of the column at the maximum load. Column shortened 1 3/4 in. at the maximum load of 456 500 lb.

8982.1

Slight spalling near top at 81 000 lb. load. Shearing started 10 in. from the top and ended 30 in. from the top. Maximum load 205 000 lb.

8982.2

Concrete appeared dry. Maximum load 210 000 lb.

8982.3

Column failed suddenly by shearing near the center, After readings had been taken at 180 000 lb. load, the load was again applied, but the column failed at178 200 lb. before 180 000 lb. was again reached. Maximum load 180 000 lb. Concrete appeared entirely dried out.

8983.1

Gradual failure. Maximum load 73 700 lb. After the maximum load

was reached, load gradually fell off to 50 000 lb.

8983.2

Concrete not entirely dry. Slow failure. Failed just below the "lower" gage points. Concrete appeared to be all right. Maximum load 62 300 lb.

8983.3

Failure by crushing about 15 in. from the bottom. Maximum load was 58 000 lb.

8984.1

Failed by crushing about 12 in. from the bottom. Maximum load 31 000 lb.

8984.2

One cylinder for this column was broken in removing the form. maximum load 26 300 lb.

8984.3

Slow failure by crushing in the lower third of the column. Maximum load 26 000 lb.

8985.1

Failed gradually by shearing at middle portion of the column. Concrete not entirely dried out. Maximum load 91 300 lb.

8985.2

Concrete was poured slightly drier than usual. Failure by crushing in the lower third. Concrete not entirely dry. Max. Ld. 109500.

8985.3

Failed by crushing along section of lower gage lines. Maximum load 95 300 lb.

2. Method of Reduction of Observed Data.— The method of reducing the strain gage data to unit deformations was that adopted as a standard by the University of Illinois Engineering Experiment Station, of which a detailed description has been given in former theses.

As several strain gages were used for these tests, each of which had a different multiplication ratio, that fact was one of the main items to be kept in mind while reducing the data. The multiplication ratio ranged from 7.5, 5,to 1.

In order to facilitate matters, the unit deformations for the same section of the column were averaged on the data sheets. The reason was two-fold. Not only was time saved in the plotting, but it will be a time-saving factor in checking the data should occasion to do this ever arise.

3. Explanation of Diagrams.— Steel. The data of the individual tests of the steel coupons were averaged and the average load-deformation curve was plotted for each size of wire used. These curves are given on pages 116 to 118.

Cylinders. The load-deformation curves for the cylinders are given on pages 62 to 76. The cylinder numbers are the same as the columns to which they belong.

Columns. The data for the load-deformation curves pp. 77 to 115 were obtained by averaging the longitudinal and the lateral deformations at all the gage lines on a given portion or section of the column for a given series. For example, all of the longitudinal readings on gage lines at a given distance from the top were averaged and the average plotted against the load. In a sim-

ilar manner the averages for all lateral gage lines at a given plane were plotted. Lateral deformations were plotted to the right of the origin, longitudinal to the left. For two of the three columns in each group deformations were read at only three sections. These are marked "Top", "Center", and "Bottom" on the diagrams. For the third column of each group, the curves for the various sections are designated by "Top","2nd.","Center", "4th", and "Bottom", respectively.

By averaging the curves of the three columns of each group, the data for the average load-deformation diagrams were obtained. Except for the top and bottom curves for the third column of each group, which were omitted altogether, deformations were read off of each curve for a given load. The average of these deformations was plotted against the load, giving the curves pp. 119 to 123 . A glance at the curves of the third column of the group will reveal the necessity of omitting the top and bottom curves from the average curves. It is obvious that the steel at these sections is not stressed nearly so much as at the three central sections.

The load-stress curves were obtained by combining the average load-deformation curves for the columns with the average load-deformation curves forthe steel. This combination was effected in a manner similar to that used for the average load-deformation curves described above. These curves are given on pp. 125 to 129 . It will be noticed that the curves pp. 126 to 129 are exactly the same as those on p. 125 . They are merely drawn to a larger scale.

The diagrams using the load at the end of the series, instead of the load at the beginning, are given on pages 113 to 116 . The average load-deformation and load-stress curves were derived in the

same way as herein before described.

Page 131 contrasts several curves. The dotted lines represent the 1-1-2 stone mix, the solid lines the 1-2-4 mix (both stone and gravel), and the dash lines the 1-3-6 stone mix. For the maximum-load-percent curves of a given mix the average of the maximum loads of the three columns in the same percent group was used. By keeping the percent constant, thesedata wereused for the maximum load-mix curves in the upper left hand corner. The load-percent curves for 0.001 lateral unit deformation, and the first-crack-load-percent curves for the different mixes are given also on this page.

On pages 132 to 147 are given some average result curves obtained by combining in various ways the average curves mentioned above. The method of arriving at these curves needs no expatiation.

4. Explanation of Tables.— Tables 1, 2, and 3, pages 7 , 8 , and 8 , respectively, are mechanical analyses of (1) stone, (2) gravel, and (3) sand. Table 4, page 8 , gives the results of the tensile tests of the neat cement and the 1-3 mortar briquettes at the ages of 7 days and 28 days. Table 5, page 10 , gives the physical properties of the steel used in the spirals. Table 7, page 148, gives the weights of the cement, sand, stone or gravel, and water used in each batch of concrete. It also compares the proportions by volume and by weight, and expresses the amount of water used as the percent, by weight, of that of the dry materials. Table 7, page 148, may be called a table of general information. It contains the various dimensions, strengths, moduli of elasticity, averages, etc. for the columns, cylinders, and spirals.

5. Explanations of Drawings.— On page 149 is a drawing show-

ing showing the location of the gage lines forthe first two columns of each group of three. The layout of the gage lines for the third column of each group is shown on page 150 . For plain columns, the location of the gage lines is shown by the drawing on page 151 .

A detailed drawing of the steel plug used for gage holes in the plain columns is shown on page 152 . The drawing is to full scale.

6. Explanation of Photographs.— Views of the shapes assumed by the columns at the maximum load carried, are shown by the photographs pages 153 to 159 . The photographs of individual columns, pages 157 to 159 , give a more detailed presentation of the failures of typical columns.

7. Analysis of Data.— It should be borne in mind in studying the results of these tests, and in comparing them with other column tests, that these columns were as straight as could be made. Moreover, the spiral reinforcement, on the whole was in good condition. So that, if one remembers the care taken in the mixing and building, he should expect the data and results obtained to be relatively reliable, even though the cement used in the tests appeared somewhat weak, reducing the ultimate strength of the concrete to values below the standard.

Considerable thought was given to the cross section that should be used for calculating unit loads. The area wanted was that which would be most representative at the stage of loading at which the spiral action was to be studied. For that stage of the loading below the ultimate of the concrete, the gross area should be used. For the maximum load carried by the column, proba-

bly the area inside the spiral should be used. But what section should be used at that stage of the loading intermediate between these, just at the bend in the load-stress curves?

To answer this question, several preliminary diagrams were drawn and tables arranged that would throw some light on it. A study of the load at first crack, load at 0.001 lateral unit deformation, and the maximum load diagrams, using both gross section and the center-to-center of the spiral in calculating the unit loads, together with the study of the following average diameters of

(1) Center-to-center of spirals,

(2) out-to-out of spirals,

(3) 1/10 in. beyond the out-to-out of spirals,

(4) half way from center point of spiral to outer point of concrete,

(5) out-to-out of concrete,

led to the choosing of (2), out-to-out of spiral, as the section that would coincide most nearly with that desired under the conditions imposed.

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From the average load-deformation curves, pages 119 to 123 , it is seen that in general for a given mix, the larger the amount of spiral the smaller are the longitudinal and lateral deformations at a given load beyond the ultimate of the concrete. Below that ultimate, the amount of spiral does not seem to affect the stiffness. A comparison of the initial moduli of elasticity, Table 7, shows this. No direct effect of the amount of spiral is seen.

A study of the load-stress curves, pages 125 to 129 , shows that for the three mixes, 1-2-4 gravel, 1-2-4 stone, and 1-3-6 stone,

the spiral unit stress at the ultimate of the plain concrete varies with the amount of spiral. For the two larger amounts, 3.5% and 6.0 %, the unit stresses practically coincide and are about twice that for the smallest amount, 1.5%. Just why this should be so is not clear. Possibly the strain gage is not sensitive enough to enable us to distinguish between the stresses at such small lateral deformations.

From page 131 it is seen that for a given mix, the variation of the maximum load with the amount of spiral is practically a straight line variation from zero to 3.5%. For the leaner mixes, 1-3-6 stone, 1-2-4 stone, 1-2-4 gravel, the equation of this line is $C'=C+1350p$, $C' = C + 1320p$ and $C' = C + 1350p$, respectively, where C is the ultimate strength of the plain concrete, C' is the maximum load carried by the column, and p is the percent spiral. For the 1-1-2 stone mix, the equation of this line is $C' = C + 920p$. From 3.5 to 6.0% the slope of the curve is less. It is about the same for the 1-2-4 gravel and 1-1-2 stone mixes, but is smaller for the 1-2-4 stone mix. Probably bending of the spiral and the crushing of the stone or gravel between the spirals are causes of the change of slope to a smaller value with an increase in the amount of spiral.

¶For a given mix, the load at first crack increases but little with an increase in the amount of spiral. The total increase from 1.5% to 6.0% is only about 350 lb. per sq.in. As long as the mixing is done consistently for the same proportioned concrete, it should be expected to crack at about the same imposed vertical load. The retardation in settling due to the spiral may account for this small variation of 350 lb. per sq.in. For the larger amounts of spiral Poisson's ratio is smaller. This would seem to indicate that the density for the larger amounts of spiral is slight-

ly less. This possibly decreased density for the larger amounts of spiral would make a slightly larger load necessary to produce the first vertical crack.

Keeping the amount of spiral constant, the average load-deformation curves show that a given load on the column produces the smallest longitudinal deformationin those containing the most cement.

A consideration of the load-stress curves page 125, reveals the fact that for columns having a given amount of spiral, the greatest spiral stress produced at the ultimate strength of the plain concrete is found in those columns composed of the richest concrete.

The maximum load-mix curves P.131 show a greater increase in load from the 1-2-4 mix to the 1-1-2 mix than from the 1-3-6 mix to the 1-2-4 mix for 0%, 1.5%, 3.5% of spiral. For these amounts of spiral, the economical advantage resulting from the use of cement as a reinforcing material is plainly revealed. For the 1.5%, it is seen that by doubling the amount of cement, i.e. using the 1-1-2 instead of the 1-2-4 mix, the maximum strength is increased 1500 lb. per sq. in. For zero percent, the maximum strength is trebled by doubling the amount of cement. As the amount of aggregate is not changed when the cement is increased, this would mean a further saving where much concrete is to be used. To double or treble the strength of the concrete would not require the using of twice the amount of concrete, but twice the amount of cement only.

The average maximum load-percent curves for the three leaner mixtures are practically parallel from zero to 3.5%. As has already

been stated, the equation of each curve is approximately $C' = C + 1350\ p$. This shows that up to 3.5% spiral, the increase in the maximum load carried by the column, per 1% of spiral is about the same irrespective of the mix.

Effect on Poisson's Ratio. As used in this thesis, Poisson's ratio means the ratio of the spiral unit deformation to the longitudinal unit deformation. Ordinarily this term applies to elastic homogeneous materials. For the convenient comparison of the relation of the above mentioned deformations, it is used in the following discussion.

From the load-reciprocal Poisson's ratio curves, pages 132 to 136, it is seen, that beginning with loads near the ultimate of the concrete, Poisson's ratio gets smaller with the increase in load until a load is reached that has stressed the steel up to or past the yield point, when the ratio gets larger again. It is significant that at some load near the ultimate of the concrete (when it has begun to fail), and at some load near or past the yield point of the steel (when it has begun to fail), Poisson's ratio is larger than for the intermediate stages when the steel is taking stress up to the yield point. It is reasonable to expect that at loads somewhere near the failure of the two materials, Poisson's ratio would be larger because of the relatively increasing rate of lateral deformation due to the breaking up of the restraint by the failure of the materials. The following table of of average values of Poisson's ratio shows the comparison for the different percents and mixes.

A consideration of this table shows that in general, for columns of a given mix, Poisson's ratio decreases with an in-

crease in the amount of spiral. This is to be expected from the increased restraint imposed by the larger amount of spiral. To obtain the same unit deformation in the larger amounts, a greater load would be necessary, resulting usually in a relatively great-

Table of Poisson's Ratios.

Percent Spiral	Poisson's ratios for the following mixes: 1-1-2 Stone	1-2-4 Stone	1-2-4 Gravel	1-3-6 Stone
0	0.12	0.12	0.17	0.05
1.5	.16	.17	.25	.12
3.5	.16	.11	.20	.07
6.o	.15	.06	.12	—

er longitudinal shortening (due to the slightly less density of the concrete in the columns containing the larger amounts of spiral), making the ratio of the lateral to the longitudinal deformations smaller for the larger amounts of spiral.

For a given percent, the table shows that the mix with the most cement has the largest Poisson's ratio. The larger the amount of spiral, the better this relation is shown. At the same time this variation is roughly shown by the plain columns. A study of the cause of this led to the conclusion that probably the greater density of the richer mixes was the main factor. For a lean mix, the load first would be expended in compressing the voids and air spaces in the concrete, pressing the particles closer together before much lateral deformation would result. It is obvious that this longitudinal shortening would be greater for the less dense, or leaner, mixtures.

For plain columns andfor loads lessthan the ultimate of the concrete in the reinforced ones, the strain gage did not seem accurate enough to determine Poisson's ratio with any reasonable

degree of consistency. Only a general trend for comparing the mixes is all that may be safely counted upon.

The longitudinal deformation—lateral deformation curves, page 138 , strikingly bring out the fact that for a given lateral deformation of a given mix, the larger the amount of spiral, the greater is the longitudinal shortening. Or in terms of Poisson's ratio: for a given mix, Poisson's ratio decreases with increase in the amount of spiral. This conclusion has already been reached from the table quoted above. The curves approach straight lines in the middle stages, beginning at about 0.001 lateral unit deformation. This means that the rate of change of Poisson's ratio is zero for this portion of the curve.

From the stress—reciprocal Poisson's ratio curves, page 137, the same general conclusions are arrived at as were obtained from the load—reciprocal ratio curves, pages 132 to 136 . These show plainly how Poisson's ratio becomes larger after the yield point of the steel has been reached. The same average Poisson's ratios, tabulated on page 36 , may be obtained from these curves except for zero percent, which is not given at all. For the 1-1-2 mix, the curves are practically straight lines above a stress in the steel of 10 000 lb. per sq.in. This is true, largely, for the other mixes, especially for the columns having the lower amounts of spiral. These lines would seem to indicate that the reciprocal Poisson's ratio varies directly with the spiral stress and Poisson's ratio itself gradually grows larger with an increase in stress, the amount depending on the slope of lines, which may vary from nearly vertical to a noticeable incline.

The percent spiral- reciprocal Poisson's ratio curves, page 139 , show that for the 1-1-2 stone and the 1-2-4 gravel mixes, there is no general law governing the variation of Poisson's ratio with the percent of spiral for a stress of 5 000 lb. per sq.in. in the steel. For these two mixes, the ratio seems not to depend upon the amount of spiral at this small stress. Whether the instrument is not accurate enough to indicate the relation at this small lateral deformation, or whether other things enter that cannot be controlled by a general law, remains yet to be determined. However, the 1-2-4 stone mix seems to show a slight decrease in Poisson's ratio with increase in amount of spiral at this small stress.

From stresses of from 10 000 to 50 000 lb. per sq. in. in the steel, there is a straight line variation of reciprocal Poisson's ratio with the percent of spiral for the 1-1-2 stone, 1-2-4 stone, and 1-2-4 gravel mixes. The bunching of the points for the given amounts of spiral for the 1-2-4 gravel mix shows the tendency for Poisson's ratio to remain constant for changes of stress for these given amounts of spiral. The tendency of the stress-reciprocal ratio curves to become vertical straight lines, noted elsewhere in this discussion, indicates the same thing,

The mix-reciprocal ratio curves found on the same page, 139, show the same inconsistency in the variation of Poisson's ratio with the mix for a given amount of spiral at a stress of 5 000 lb. per sq. in. in the spiral. For stresses from 10 000 to 50 000 lb. per sq. in. in the spiral, however the ratio increases with an increase in the amount of cement, and the relation is roughly a straight line, especially for 3.5% spiral. Quite a con-

trast is presented by the bunching of the points for 1.5% spiral, and the spreading out of the points for the 3.5% spiral of the 1-3-6 mix. The stress-reciprocal ratio curves, page 137, show this also. For the 1.5%, the curve is a vertical line, nearly, but for the 3.5% it is rather erratic.

L <u>Miscellaneous</u>. While the load-mix curves, page 140, do not show a straight line variation at a given stress for a given amount of spiral, they do show that for a given stress, an increase in load accompanies an increase in amount of cement. For stresses in the spiral above 10 000 lb. per sq. in., these curves are parallel nearly, indicating a given increment of load for a given increment of stress, irrespective of mix. For a given mix, the additional load for an increase of 10 000 lb. per sq.in. stress, is nearly a constant. This is shown more clearly in other curves.

On this same page are the longitudinal deformation-mix curves. They show that for a given amount of spiral and at a given stress, the leaner mixes have the larger longitudinal deformations.

The longitudinal deformation-percent curves for a given mix and at various spiral stresses, page 141, are roughly straight lines. The relation between the longitudinal deformation ϵ, the amount of spiral, p, and the spiral stress f_s, for the 1-2-4 stone mix is given by the following equations.

$$f_s = 20\,000, \quad 6\epsilon - .01p - .0105 = 0$$

$$f_s = 30\,000, \quad 6\epsilon - .016p - .0105 = 0$$

$$f_s = 40\,000, \quad 6\epsilon - .022p - .0105 = 0$$

Combining these we have

$\varepsilon = .00175 + p\left(\frac{f_s - 3333}{10\,000\ 40\nu}\right)$

$$6\epsilon - .01\,p - .0105 - \left[\frac{f_s - 20\,000}{10\,000}\right].006p = 0 \quad \ldots\ldots \text{ A}$$

The equation A is a general equation for the relation between ϵ, p, and f_s for stresses in the spiral of from 20 000 to 50 000 lb. per sq.in. Equations similar to A may be derived for the other mixes. At a stress of 50 000 lb. per sq. in. these curves deviate noticeably from straight lines. In general this straight line variation lies between stresses of 10 000 and 50 000 lb. per sq. in. For the 1-2-4 stone mix, instead of passing through zero, the lines intersect at about .00175 longitudinal unit deformation on the zero percent line. From this it seems that at all amounts of spiral the longitudinal unit deformation is a constant at the stage when the spiral begins to take stress.

The additional load-percent curves for a given mix and at various spiral stresses P.142, were obtained by using the following ultimates for the plain mixes.

Mix.	Ultimate Strength
1-1-2 Stone	3350 lb. per sq. in.
1-2-4 Stone	1100 do.
1-2-4 Gravel	1650 do.
1-3-6 Stone	500 do.

The curves are approximately straight lines, showing a proportional increase in additional load with an increase in the amount of spiral. Most of the lines for a given mix intersect on the zero percent line. This intersection is at about 1000 lb. per sq. in. added load for the 1-1-2 stone mix; 500 lb. per sq.in. for the 1-2-4- stone mix; and 750 lb. per sq.in. for the 1-2-4 gravel mix. Equations showing the relation of the added load, L,

the amount of spiral, p, and the spiral stress , f_s, for the 1-1-2 stone mix are:

For $f_s = 20\ 000$, $6L - 970\,p - 6\ 000 = 0$

$f_s = 30\ 000$, $6L - 1450p - 6\ 000 = 0$

$f_s = 40\ 000$, $6L - 1850p - 6\ 000 = 0$

$f_s = 50\ 000$, $6L - 2250p - 6\ 000 = 0$.

The following general equation, showing the relation of L, p, and f_s, is derived by combining the above equations:

$$6L - 970p - 6\ 000 - \left[\frac{f_s - 20\ 000}{10\ 000}\right] 410p = 0 \quad . \ . \ \underline{B}$$

This equation B applies only between 20 000 and 50 000 lb. per sq.in. stress in the spiral.

The following are similarly derived equations for the 1-2-4 gravel mix;

$f_s = 20\ 000$, $6L - 1500p - 4500 = 0$

$f_s = 30\ 000$, $6L - 2200p - 4500 = 0$

$f_s = 40\ 000$, $6L - 3000p - 4500 = 0$

$f_s = 50\ 000$, $6L - 3900p - 4500 = 0$

from which equation C is derived, which pertains only to stresses in the spiral between 20 000 and 50 000 lb. per sq.in.

$$6L - 1500p - 4500 - \left[\frac{f_s - 20\ 000}{10\ 000}\right] 800p = 0 \ldots . \ \underline{C}$$

Equations for the 1-2-4 stone mix are

$f_s = 20\ 000$, $6L - 1700p - 3000 = 0$

$f_s = 30\ 000$, $6L - 2400p - 3000 = 0$

$f_s = 40\ 000$, $6L - 3100p - 3000 = 0$

$f_s = 50\ 000$, $6L - 3800p - 3000 = 0$

and the general equation is

$$6L - 1700p - 3000 - \left[\frac{f_s - 20\ 000}{10\ 000}\right] 700p = 0 \ldots\ldots \underline{D}$$

The graphs for these general equations practically coincide with the curves plotted from the test data.

It is noticed that for each mix the curves intersect on the zero percent line. This intersection is at an added load of 1000 lb. per sq.in. for the 1-1-2 stone mix; 750 for the 1-2-4 gravel mix; and 500 for the 1-2-4 stone mix. An ordinary assumption would be that these curves, if intersecting on the zero percent line, would do so at the ultimate of the plain concrete. The explanation is offered that something of the like actually occurs. Instead of considering the ultimate strength of concrete in the reinforced columns to be slightly less than that of the plain concrete columns as is customary, it seems plausible from the consistency of the curves of the different mixes and from a consideration of the possible effect of the spiral restraint, that the ultimate strength of the concrete in the reinforced columns should be based on this point of intersection rather than on the strength of plain columns.

One reason advanced for taking the ultimate of the concrete for the reinforced columns to be less than the ultimate of the plain concrete, is that in general the initial modulus of elasticity is greater for the plain column than for the reinforced one. For a given mix this is not necessarily a criterion, and in spirally reinforced columns, where the interference of the spiral decreases the density of the concrete, it seems possible that the effect on the strength of the concrete due to this decreased density could be more than accounted for by the effect of the restraint afforded by the spiral in aiding the concrete to adhere. At the same time the smaller initial modu-

lus of elasticity of the reinforced column could be ascribed to this decreased density.

If this is the case, it seems logical that the working load should be based on this so-called "ultimate" of the concrete. It should be noted that as these curves are straight lines for a given stress, the additional load from the point of intersection varies directly as the amount of spiral. The fact that these curves do intersect in a common point on the zero percent line shows that the so-called increase in the ultimate strength of the concrete above that of the plain concrete is the same for the small as for the large amounts of spiral.

As this increase is greatest for the 1-1-2 mix, it would seem advantageous to adopt this mix, with 1% of spiral for commercial designs. The use of this mix would allow larger working loads, economical if based on this so-called "ultimate". Then too, the small amount of spiral would be as effective as larger amounts at these working loads.

Some column formulas for working loads consider the amount of spiral. Others base the design load on the maximum load the column will carry. These additional load-percent curves seem to show that it is not entirely correct to base the working load formula on either the amount of spiral or the maximum load. They both vary, while this value for the ultimate of the concrete is a constant for columns of a given mix.

Interest is aroused by the fact that the "bend" of the load-longitudinal deformation curves for a given mix comes very near the load designated by the point of intersection of the additional load-percent curves. Or we may say that the relation of these

so designated loads to the load-longitudinal deformation curves is similar to that of the yield point to steel load-deformation curves. For this designated load, the longitudinal deformations for the curves of a given mix are about the same for the various amounts of spiral. For the 1-2-4 stone mix this average deformation is about .00175. It has been stated previously that for this mix, the longitudinal deformation-percent curves intersect at this deformation of .00175. This is significant in that the point of intersection occurs at a deformation that corresponds to the "yield point" of the column. Also, this further emphasizes the fact that the so-called load carried by the concrete is independent of the amount of spiral. The sharpness of the bend of the load-deformation curves does depend on the amount of spiral. For the smaller amounts, the portion of the curve past the bend is flatter than for the columns having the larger amounts of spiral. This is to be expected.

In regard to the factor of safety, Considere says "The logical conclusion would be the adoption for hooped concrete of a factor of safety smaller than that generally used for metal structures, which varies between 2 and 2.5 on the basis of the elastic limit and of the column resistance. . . . . But hooped concrete has an indisputable drawback; it represents a novel method of construction which has not stood the test of years. For this reason the author proposes a factor of safety of 3 to 3.5 for hooped concrete structures".

One thing not to be overlooked in choosing a safe working load, is the longitudinal shortening of the column. This should enter into a determination of the factor of safety. For the

1-1-2 mix, using the average longitudinal deformation for the "yield point" of 4350 lb. per sq.in. (which is the load designated by the additional load-percent curves) the shortening of a 10 ft. column would be 0.3 in. at that load. This shortening would not necessarily entail the failure of a structure dependent on the column. A factor of safety of 3.5 would mean a working load of 1250 lb. per sq. in. with a total shortening of 0.05 in. for a 10 ft. column. This factor of safety for spirally reinforced columns of 1-1-2 mix seems conservative enough to suit the most fastidious. Moreover, this working stress of 1250 lb. per sq.in., while high compared to that ordinarily used, does not seem too large from the light thrown on spiral action by these tests.

The spiral unit stress-percent curves for a given added load page 144, show a general trend to a point of intersection at some given amount of spiral. This amount of spiral varies with the mix. The character of the curves, too, varies with the mix. For the 1-2-4 stone mix, they are concave upward. For the 1-2-4-gravel mix they are concave upward from the given additional load of 1500 lb. per sq. in. and up; up to a given load of 1500 lb. per sq.in. the curves are convex upward. In general the shape of the curves of the 1-1-2 stone mix is similar to that of the 1-2-4 gravel mix. Evidently the shape depends on the stiffness of the columns. The fact that there is a tendency for the curves to intersect at a common point seems to indicate that beyond a certain amount of spiral, any further increase in the amount of spiral will not increase the maximum load carried by the column. This amount of spiral varies with the stiffness of the column, the hardness of the stone or gravel, and the homogeneity

of the concrete. For the 1-2-4 stone mix, which seems fairly homogenous, the amount of spiral beyond which the effect on the maximum load would not be increased is around 7.5%. The particles will stand only a certain amount of pressure before local crushing and bending occur. The becoming acquainted with these facts makes obvious the uselessness of the reinforcement beyond a given amount.

From the conclusions of former tests it seemedreasonable to expect for columns of a given mix, if they are homogenous, that at a given longitudinal deformation the total stress in the spiral (and hence the total lateral pressure) would be a constant for the different amounts of spiral. The stress-percent curves for a given longitudinal deformation, page 145 , show this not to be true in general. For the 1-2-4 stone mix, the equations on page 40 , show this to be true within certain limits of spiral stress. Also, for this mix, whose properties, by way of parenthesis, seem to be the most consistent of any of the mixes, there is practically a straight line variation of the stress with the amount of spiral. These lines are closely parallel. Their equations are:

1-2-4- Stone Mix.

$$\epsilon = .003, \qquad f_s + 5050p = 59\ 000.$$

$$\epsilon = .004, \qquad f_s + 5050p = 64\ 000.$$

$$\epsilon = .005, \qquad f_s + 5050p = 69\ 000.$$

and the general equation is

$$f_s + 5050p = 59\ 000 + \left[\frac{\epsilon - .003}{.001}\right] 5\ 000$$

Between the limits of longitudinal deformation used in these equations, they show that the increase in stress for a given

change of longitudinal deformation is independent of tha amount of spiral.

After seeing that the total spiral stress was not a constant for a given longitudinal deformation of a given mix, the question arose, for what given property is the total stress the same? Referring back to the additional load-percent curves, page 142, the discovery was made that for a given additional load, the product of the unit stress by the amount of spiral is a constant. In ascertaining why this should be so, it was concluded that for a given added load - or a given total load, for that matter - as the longitudinal deformation is greatest for the smallest amount of spiral, the lateral expansion likewise should be greatest. This would mean the greatest unit stress for the least amount of spiral at a given added load. It is conceivable that the product of the large stresses by the small amounts of spiral could be the same as the product of the smaller stresses by the larger amounts of spiral. On the other hand, above a certain longitudinal deformation, a given increment of longitudinal deformation probably would mean a given change in lateral deformation - that is, for all amounts of spiral, a given change in longitudinal deformation would cause a given change in spiral unit stress. Hence the larger the amount of spiral, the greater would be the total lateral stress for a given longitudinal deformation. These conclusions are borne out by the curves.

The following table shows the striking coincidence of the constant total stress for a given added load and mix.

<u>0.001 Lateral Unit Deformation Curves</u>. The additional load-percent curves for this 0.001 lateral unit deformation,

Added Load of 2000 lb. per sq. in.			
Mix	Stress, f_s	Percent, p	Product, pf_s
1-1-2	50 000	2.44	122 000
do.	40 000	3.10	124 000
do.	30 000	4.20	126 000
do.	20 000	6.30	126 000
1-2-4	50 000	2.20	112 000
Stone	40 000	2.80	112 000
do.	30 000	3.70	111 000
do.	20 000	5.30	106 000
1-2-4	50 000	2.00	100 000
Gravel	40 000	2.50	100 000
do.	30 000	3.30	99 000
do.	20 000	5.10	102 000

page 143, again calls attention to the point of intersection of these curves on the zero percent line, already discussed. These curves, which are straight lines, nearly, cut the zero percent line at the same additional loads as do the similar curves for given stresses. Being below the lateral deformation to which the elastic limit of the steel corresponds, this deformation of 0.001 may be interpreted as a given stress - in which case these curves would be of exactly the same nature as those on page 142.

The unit load-percent curves, page 147, are of exactly the same nature as the additional load-percent curves mentioned above. They differ only by the constants assumed for the ultimate strengths of the plain concrete. It is noticed that these curves, which are straight lines, consistently cut the zero percent line at a unit load that is the sum of the loads assumed for the strength of the plain concrete plus the additional load given by the additional load-percent curves for the 0.001 unit deformation.

The unit load-mix, and the longitudinal deformation-mix curves found on page 147, are the same as the similarly titled curves for stresses of 20 000 and 30 000 lb. per sq. in. page 140.

The longitudinal deformation–percent curves for the different mixes, found on this page are straight lines, approximately, the one for the 1–2–4 mix being very close to a straight line.

Stone vs. Gravel Concrete. (a) Moduli of Elasticity. For the plain columns, the moduli of elasticity are about the same. The reinforced columns, however, show a larger modulus for the gravel than for the stone concrete: 2 800 000 vs. 1 800 000 lb.per sq.in.

(b) Strengths. The following table is a comparison of the strengths at maximum load, load at first crack, and load at 0.001 lateral unit deformation.

Kind	Percent	Max. Load	First Crack	0.001 Deformn.
Stone	0	1200	—	—
	1.5	3440	2035	2140
	3.5	5800	2120	2900
	6.0	6610	2645	4000
Gravel	0	1850	—	—
	1.5	3880	2710	2900
	3.5	6690	2975	3570
	6.0	8410	2985	4720

A study of this table shows gravel concrete to be stronger, tougher, and stiffer. For the columns containing 6% spiral, the gravel shows a relatively greater increase in strength than does the stone. One reason for this is that the greater stiffness of the gravel concrete together with the increased hardness of the gravel over the stone, enabled it to delay the bending action of the column longer than did the stone. The curves for the maximum strengths, page 131 , show this clearly. For the first part of the curves, the additional strength per percent of spiral was about the same, the gravel, however, having the greater strength for plain columns. The additional load for a given stress and amount of spiral is about the same for each kind. With 6% spiral, the

average unit additional load for the gravel between the stresses of 20 000 and 50 000 lb. per sq.in. is 800 lb. per sq.in.; for the stone it is 700 lb. The "yield point" of the gravel is 2400 lb. per sq.in.; for the stone columns it is 1600, an increase of 750 lb. per sq. in. above that assumed as ultimate for plain gravel concrete, and 500 lb. per sq.in. above that assumed for the stone.

Poisson's Ratio. The table of ratios page 36 , shows Poisson's ratio to be larger for the gravel than for the stone. This is to be expected when the greater stiffness of the gravel concrete is taken into consideration.

On the whole, the various resultant curves for the two mixes are rather consistent. Those for the stone mix seem to be the more so. It is noticed that quite often similar curves for the t two mixes have opposite tendencies. Where those for the one are concave upward, those for the other are likely to be convex upward. To some extent, the greater strength and stiffness of the gravel mix is responsible for this. It seems, then, that a larger factor of safety for the same working stress, or else a larger working stress for the same factor of safety would result from using the gravel. For investigational purposes, it is likely that the stone mix would give more consistent results.

Theory of Hoop Action. It is only after the loading has passed that stage which corresponds to the ultimate strength of the plain concrete that the spiral is stressed to any great extent. By exercising care in choosing the values for the different factors in the formula $f_s = \dfrac{\mu f'_c}{\frac{1}{n} + \frac{p}{2}(1-\mu)}$, derived for the

value of the steel stress when the concrete is an elastic material (i.e. for loads under the strength of plain concrete), page 5, something like the actual stress in the spiral is obtained. These stresses are very low. Of course it must be remembered that for such low stresses the errors introduced into the readings by the inaccuracy of the strain gage would have considerable influence on the amount of the stresses actually found, To a great extent, this could account for the variance between the actual and the theoretical stresses.

Considere, in his admirable book on reinforced concrete, treats the concrete as a granular material at the maximum load on the column. In his derivation of an expression to represent the part played by the spiral reinforcement, he obtained the ratio of load added by the spiral to that added by an equal amount of longitudinal reinforcement, to be $\frac{K}{2}$, where K is $1/\tan^2\frac{\phi}{2}$ and ϕ is the complement of the angle of internal friction of the concrete. Considere assumed a constant value of 4.8 for K for all loads and arrived at the conclusion that "The resistance given to concrete by the hooping is 2.4 times greater than the direct resistance of the longitudinal reinforcing members of the same weight when the tensile stress in the former is equal to the compressive stress in the latter".

Using this value of 2.4, with the yield point of the steel and the ultimate of the plain concrete in the following formula for maximum unit stress, $\frac{P}{A} = f_c + 2.4\ pf_s$, the results tabulated below show the comparison of this with the actual maximum, for the different mixes and percents.

Mix	Percent	Actual Max.	Theoretical Maximum	Percent Diff.
1-1-2	1.5	5060	5480	+8.3
Stone	3.5	6850	7630	+11.3
	6.0	8420	10470	+24.3
1-2-4	1.5	[illegible]440	3000	-14.6
Stone	3.5	5800	5150	-11.2
	6.0	6610	8260	+25.0
1-2-4	1.5	3880	3700	-4.7
Gravel	3.5	6690	5850	-12.5
	6.0	8410	8900	+5.7

It is seen that the difference between the two increases with the increase in the amount of spiral. Later, reason will be advanced to show that this is as it should be.

It seems that the principle of granular action adopted by Considere is fundamentally correct for loads that stress the spiral to any great extent. Issue is taken, however, with the assumption of a constant value for the coefficient of internal friction — or what is the same thing, in assuming K to be 4.8. Before discussing the fallacy in the assumption of a constant value for the coefficient of internal friction, the following table is offered for the 1-2-4 stone mix and 3.5% spiral, which is typical of other mixes and amounts of spiral.

Spiral Stress	P	q	P-q	P+q	$\frac{P-q}{P+q}$	ϕ	$\frac{q}{P} = \frac{1}{K}$
10 000	840	175	665	1015	.656	41.0°	.208
20 000	1400	350	1050	1750	.600	36.5	.250
30 000	1860	525	1335	2385	.560	34.0	.282
40 000	2260	700	1560	2960	.527	31.7	.309
50 000	2800	875	1925	3635	.529	52.[illegible]	.312
60 000	3900	1050	2850	4950	.577	41.3	.270

In this table, P = vertical unit added pressure
q = lateral unit pressure = $pf_s/2$
ϕ = angle of internal friction = $\sin^{-1} P-q/P+q$
p = steel ratio.

This table shows that for a given mix and given amount of spiral, the coefficient decreases with an increase in vertical load until the yield point of the steel is reached, when it begins to increase. This is contrary to the assumption of a constant coefficient of internal friction by Considere.

The most likely explanation that presents itself is that in the earlier stages of the loading, before the concrete has become so completely disintegrated as would be expected for higher loads, the cohesion helps to make the coefficient of internal friction higher than at later stages. From the nature of concrete it would seem that with the increasing vertical pressure destroying the cohesion and breaking up the concrete more and more, the friction of the particles on each other would approach a constant, decreasing the angle of friction less and less rapidly as the load increased. It would be supposed that at some load the concrete would be so broken up that any further increase in load would not materially affect the angle of friction. This seems to be the case. It is noticed that the change in the angle becomes less and less with a given change in stress until the yield point of the steel is passed.

A comparison of the table below with that on page 52, shows that for the same spiral stress, the leaner mixes have smaller angles of internal friction. When it is remembered how much more rapidly the lean mix columns shorten for a given additional load, breaking down the cohesion relatively more, they would be expected to have smaller angles of friction.

Although Considere used a constant coefficient of friction, he had some idea of the varying effect of the cohesion as may be

1-3-6 Stone Mix, 3.5%

Spiral Stress	P	q	P-q	P+q	$\frac{P-q}{P+q}$	ϕ	$\frac{q}{P}\frac{1}{K}$
10 000	700	175	525	875	.600	36.9° 36.5°	.250
20 000	1250	350	900	1600	.563	34.2	.280
30 000	1750	525	1225	2275	.538	32.5	.300
40 000	2340	700	1640	3040	.538	32.5	.300
50 000	2800	875	1925	3675	.524	31.5	.312
60 000	4000	1050	2950	5050	.584	35.5	.265

gathered from the following which is quoted from his book: "The modification which cohesion will cause in the effects of friction cannot be easily predicted, and the conclusions drawn as to the ~~A~~ non-cohesive bodies are of interest only in so far as they permit, in the absence of an exact theory of hooped concrete, the deduction of sufficient rules for the computation of its resistance and coefficient of elasticity". So it seems that after all, Considere was using a makeshift formula in the absence of further data on the subject.

A peculiar change in the angle of friction takes place at a stress corresponding to the yield point of the steel. Beyond the yield point, the angle grows larger. The decreasing increment seems to have approached zero at about the yield point and become positive beyond it. The reasons for this are obscure. It may be that after the yield point has been reached, the relatively greater lateral expansion for a given increment of load causes more internal work to be done because of this greater distance to be traveled due to the increasing rate of expansion. And as a given additional restraint is required for a given additional vertical load, this increased internal resistance would furnish a relatively larger amount of restraint, leaving a relatively less amount to be furnished by the spiral. As the angle of inter-

nal friction is a direct function of the lateral pressure due to the stress in the spiral, ($\phi = \sin^{-1} \frac{P-q}{P+q}$), any relative decrease in this lateral stress for a given increment of loading would mean a larger angle of internal friction, even if at first the coefficient of friction was constant but the internal work was increased due to an increase in lateral expansion. This, together with the more roughened surfaces due to the more rapid disintegration of the concreteafter the yield point of the steel has been reached seems the best explanation for this variance in the coefficient of internal friction.

With the light thrown on hooped column action by the changing coefficient of internal friction, it is clear why the load-stress curves should take an upward trend at the higher stresses. As long as the change in the coefficient of friction is constant for a given change in stress, the change in the curve should be the same. But if the change in the coefficient is relatively less and less, then the change in the load-stress curve should be less and less until finally the curve should take an upward trend. This upward tendency will be more sharply accentuated if the change in the coefficient of friction passes through zero and becomes of an opposite sign. Even if the coefficient were to become constant, i.e., if the change did not become of an opposite sign, this upward tendency for the largest amounts of spiral would be marked.

The upward trend of the load-stress curves for the small amounts of spiral is not so pronounced. The load for a given stress is smaller; the concrete has more cohesion, then, for this given stress. Too, the rate of change of the coefficient of fric-

tion is more nearly a constant; the relative increase in internal work at a given stress is probably less. These would account for the decreased upward tendency of these curves at high stresses.

It was thought at first that the load at the beginning of the series, used for calculating the load on the column, was not as near to the correct load as the one to which the load had dropped at the end of the readings. It seemed probable that the spiral had not become fully adjusted to the newly imposed load prior to the taking of the strain gage readings. Consequently, curves were plotted for the 1-2-4 stone mix using the load at the end of the series. These curves, page 130, show if anything, a more pronounced upward trend. This, then, did not explain the reduced increase in stress for a given increase in load. Another explanation was then sought, resulting in the discovery of the varying coefficient of friction, with the above deductions.

It is hoped that further tests will be made to verify the explanation of hoop action offered here.

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It was seen from the table, page 52, that the difference between the actual strength developed by the column and the theoretical strength given by the formula $P/A = f_c + 2.4pf_s$, increased with an increase in the amount of spiral for a given mix. The following table of 1-2-4 stone mix shows an increase in 1/K or a decrease in K/2 with an increase in the amount of spiral.

Of course where bending affects the maximum load carried by the column, the use of a constant value for K/2 in formulae for maximum strengths would make a greater relative variation between the actual and theoretical maximum loads for columns having large

amounts of spiral, because the bending would be relatively greater.

1-2-4 Stone.

Spiral Stress	1/K for			K/2 for		
	1.5%	3.5%	6.0%	1.5%	3.5%	6.0%
10 000	.125	.208	.254	4.0	2.4	2.00
20 000	.171	.250	.272	2.9	2.0	1.85
30 000	.223	.282	.313	2.3	1.8	1.60
40 000	.280	.309	.345	1.8	1.65	1.45
50 000	.318	.312	.360	1.6	1.60	1.40

That the difference is greater for large amounts of spiral when the constant 2.4 is used means in this case, however, that this constant happened to be closer to the value given by the coefficient of friction for the small amount of spiral at the time the column failed.

For the small amounts, the actual strength developed is greater than the theoretical. For the largest amount the reverse is true. The values of K/2 for a stress in the spiral of 50 000 lb. per sq. in. show that in the one case 2.4 is too small and in the other too large.

Instead, then, of using 2.4 in the formula $P/A = f_c + 2.4pf_s$, it seems logical to vary the value of this constant with the mix and amount of spiral.

7. Summary.- The following is a summary of the conclusions drawn from a study of the tests:

1. For columns of a given mix, the value of the initial modulus of elasticity is independent of the amount of spiral reinforcement and is less than that for plain concrete columns. This difference is most pronounced for the lean mixes. For the 1-2-4 stone concrete and 1-3-6 stone concrete, the initial modulus of elasticity of the hooped columns is about 30% smaller than for

the plain columns. For the 1-1-2 stone concrete and 1-2-4 gravel concrete the initial modulus of elasticity of the hooped columns is very little, if any, less than for the plain columns.

2. At a load corresponding to the ultimate strength of plain concrete, the unit stress developed in the spiral is greater in the columns having the larger amounts of spiral. This spiral unit stress is also greater in the columns with the richer mixture.

3. For the maximum load carried by the column, the added s strength per one percent of spiral reinforcement (up to 3.5%) is a constant, 1350 lb. per sq.in., for the 1-2-4 gravel concrete, 1-2-4 stone concrete, and 1-3-6 stone concrete.

4. For columns of a given mix, the load at the first observed vertical crack is practically independent of the amount of spiral. The corresponding lateral unit deformations are practically the same at the time these first vertical cracks are noted, averaging .00035 in./in. for 1-1-2 stone concrete, .0005 in./in. for the 1-2-4 stone concrete, and .0004 in./in. for the 1-3-6 stone concrete.

5. For a given added load (beyond the load corresponding to the strength of plain concrete), there is no general law governing the variation of longitudinal unit shortening with a variation in the amount of cement.

6. Poisson's ratio in the hooped concrete columns is larger at the ultimate strength of plain concrete and beyond the yield point of the spiral steel than it is for intermediate stages. Above a stress of 10 000 lb. per sq. in. in the spiral, Poisson's ratio increases somewhat with the spiral unit stress, being nearly a constant up to the yield point of the steel.

7. For columns of a given mix at loads above the ultimate for plain concrete, Poisson's ratio decreases with an increase in the amount of spiral. For columns having a given amount of spiral, Poisson's ratio increases with an increase in the amount of cement.

8. The strain gage can not be used for an accurate determination of Poisson's ratio for plain concrete columns, or for loads less than the ultimate strength of the concrete itself in the reinforced columns.

9. For columns of a given mix, the larger the amount of spiral reinforcement, the greater is the longitudinal shortening required to produce a given lateral deformation.

10. The longitudinal unit deformation required to produce a stress in the spiral of 5 000 lb. per sq. in. is practically independent of the amount of spiral.

11. For stresses in the spiral less than 50 000 lb. per sq. in., the longitudinal unit deformation of the column varies directly with the amount of spiral. But it does not approach zero as the amount of spiral approaches zero.

12. For given spiral unit stresses less than 50 000 lb. per sq. in., the added strength of the hooped column due to the spiral increases directly with the amount of spiral reinforcement.

13. In spirally reinforced concrete columns, the load carried by the columns up to the stage of loading where hoop action begins is greater than the ultimate strength of the plain concrete columns. This load carried by the concrete in the spirally reinforced columns is approximately the yield point of the column, and for a given mix it is independent of the amount of spiral.

14. From an exterpolation of the curves for columns of a given mix, it seems that as the amount of spiral is increased, a value is approached beyond which any further increase in the amount of spiral does not increase the maximum load carried by the column. For the 1-2-4 stone concrete this value is about 7.5%.

15. For columns of the 1-2-4 stone concrete, the increase in spiral stress for a given change in the longitudinal shortening is practically independent of the amount of spiral.

16. For columns of any mix, below a spiral stress of 50 000 lb. per sq. in., the total lateral pressure on the column due to the stress in the spiral depends only upon the added load, and is independent of the amount of spiral.

17. Gravel concrete columns have larger initial moduli of elasticity, higher loads at first vertical crack, and carry greater loads at the maximum, than do stone concrete columns of the same amount of spiral and same proportioned concrete. About the same additional load is required to produce a given change in unit stress in the spiral for the two aggregates. Gravel seems the better for commercial use, stone for investigational purposes.

18. For commercial purposes, columns of 1-1-2 stone concrete seem the most economical, within certain limits.

19. Working loads should be based on the "yield point" of the columns. In choosing working loads, the corresponding longitudinal deformation should be taken into consideration. With a factor of safety of 3 to 3.5, a working load based on the "yield point" generally would be higher than is ordinarily used.

20. The coefficient of internal friction of a spirally reinforced concrete column decreases at a decreasing rate until after the yield point of the steel has been reached, when it begins to increase. The amount of this increase depends on the amount of spiral.

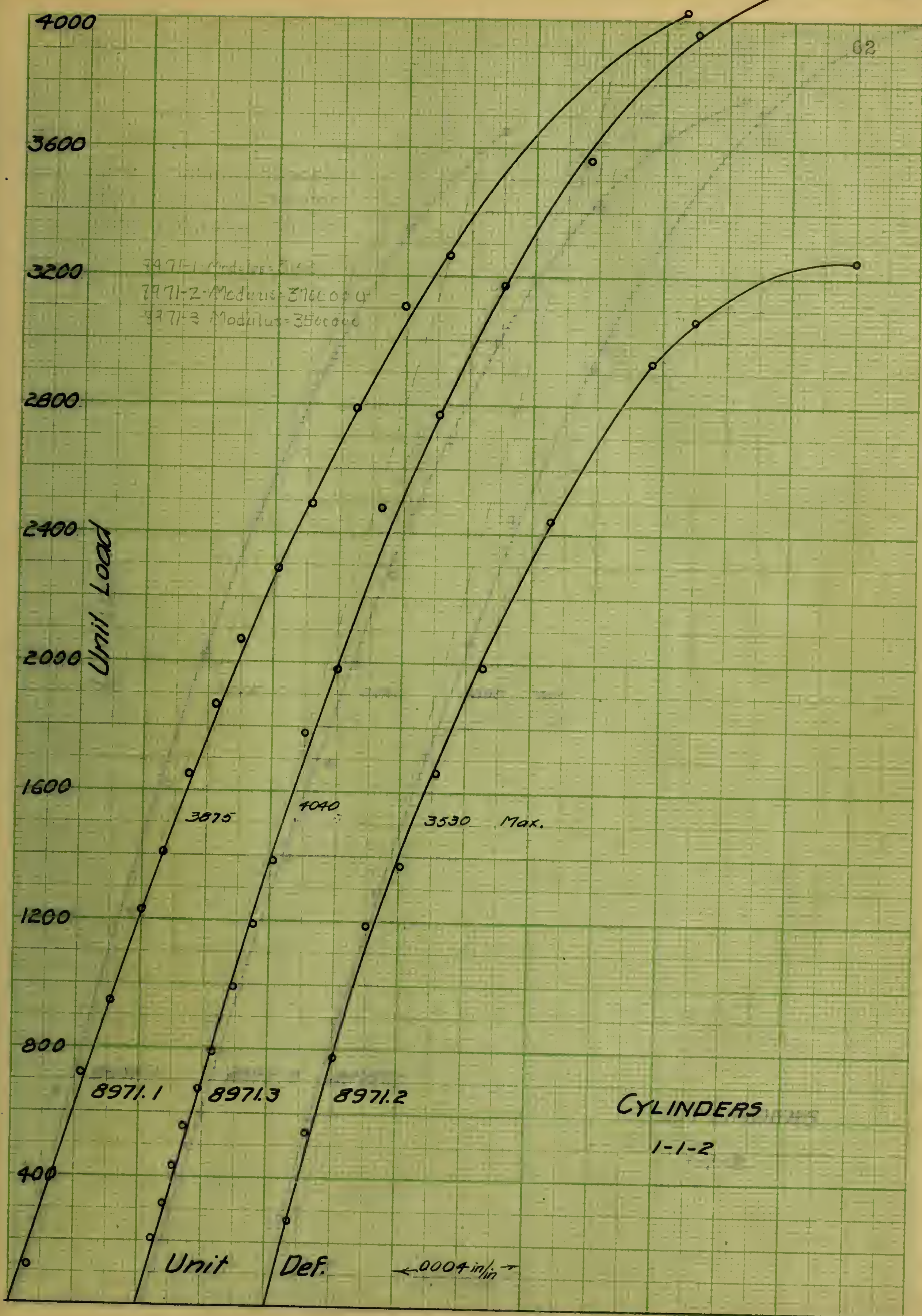
21. For columns of a given mix, at a given spiral stress the coefficient of internal friction decreases with an increase in the amount of spiral.

22. For columns having a given amount of spiral, at a given spiral stress the coefficient of internal friction decreases with a decrease in the amount of spiral. ?

23. In the formula for maximum unit load, $P/A = f_c + Kpf_s$, the value of K depends on the mix and the amount of spiral.

24. Conclusions 1, 6, 10, and 11 agree with Mr. Thomas' thesis, '14. Conclusions 2 and 16 differ from his. Although not especially emphasized in the above, these tests lead to the following conclusions which are contrary to those obtained by Mr. Thomas: (1) The added strength required to produce a given change in the spiral unit stress is not a constant for the different mixes. (2) After the spiral begins to take stress, the load-stress graph is a gentle curve for any mix or amount of spiral.

CURVES



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4000
3600
3200
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2000
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Unit Load
8971-2 Modulus=3760000
8971-3 Modulus=3560000
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CYLINDERS
1-1-2
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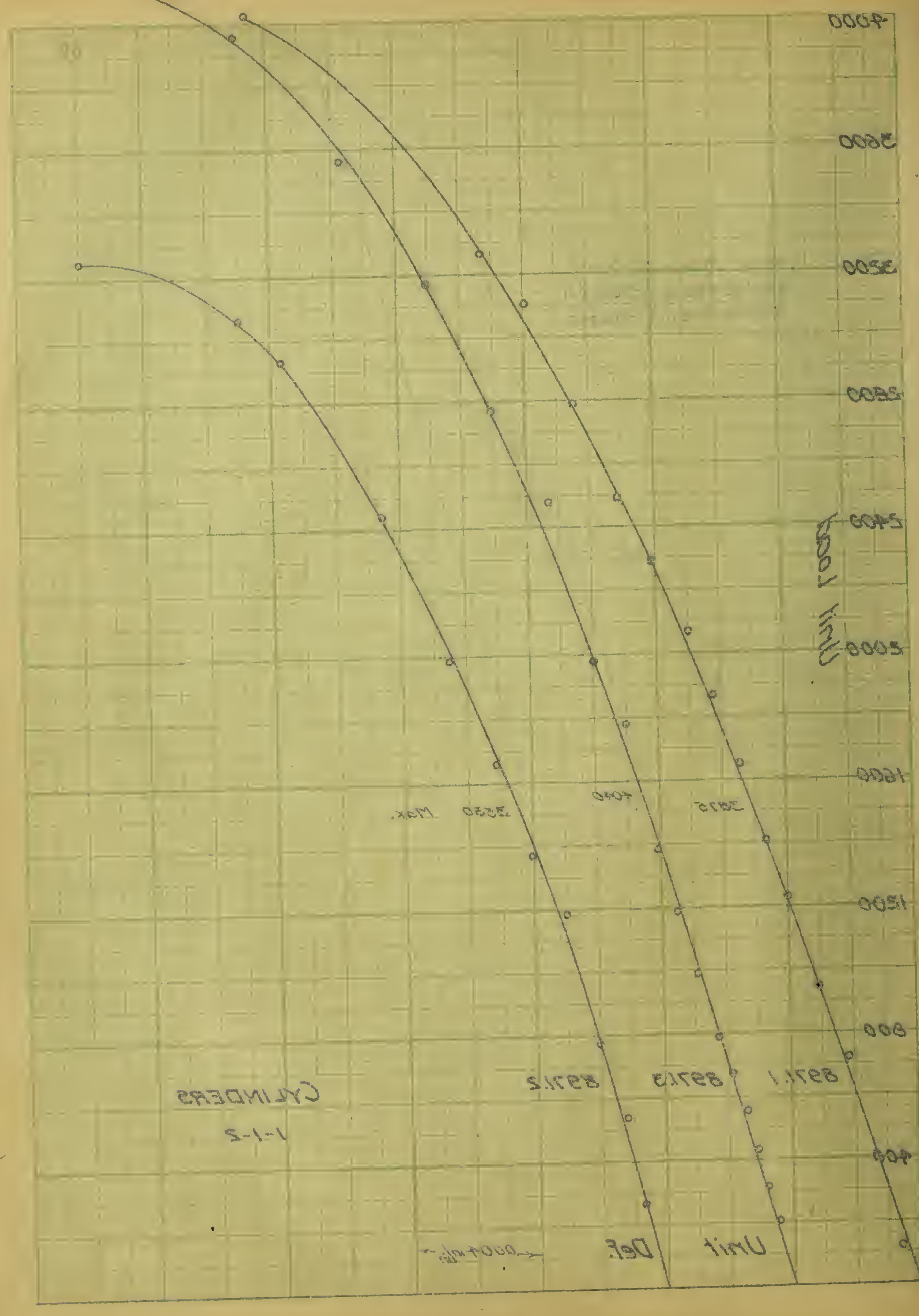

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Unit Load
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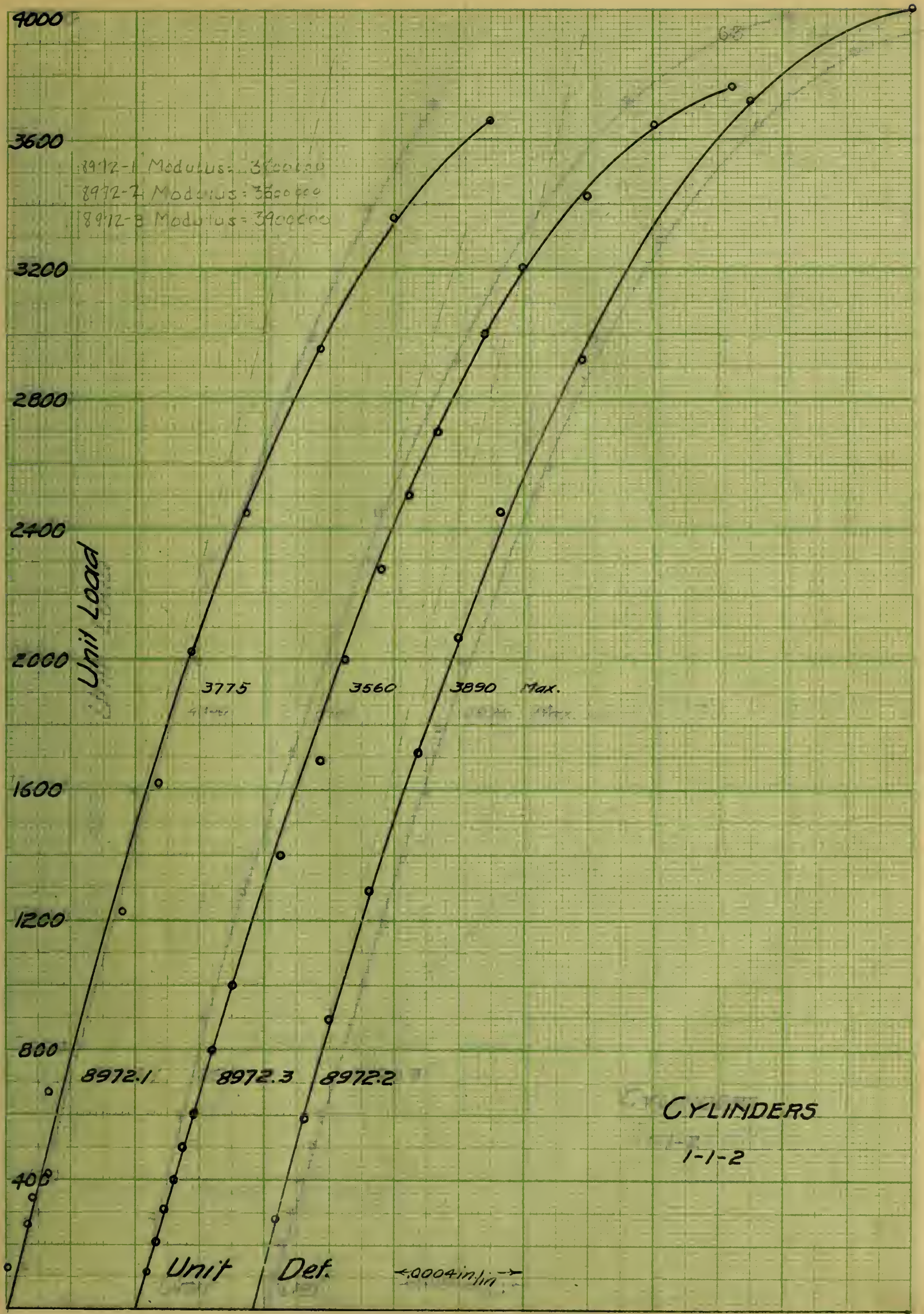

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8972-1 Modulus = 3800000
8972-2 Modulus = 3600000
8972-3 Modulus = 3900000
Unit Load
3775
3560
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CYLINDERS
1-1-2
Unit Def.
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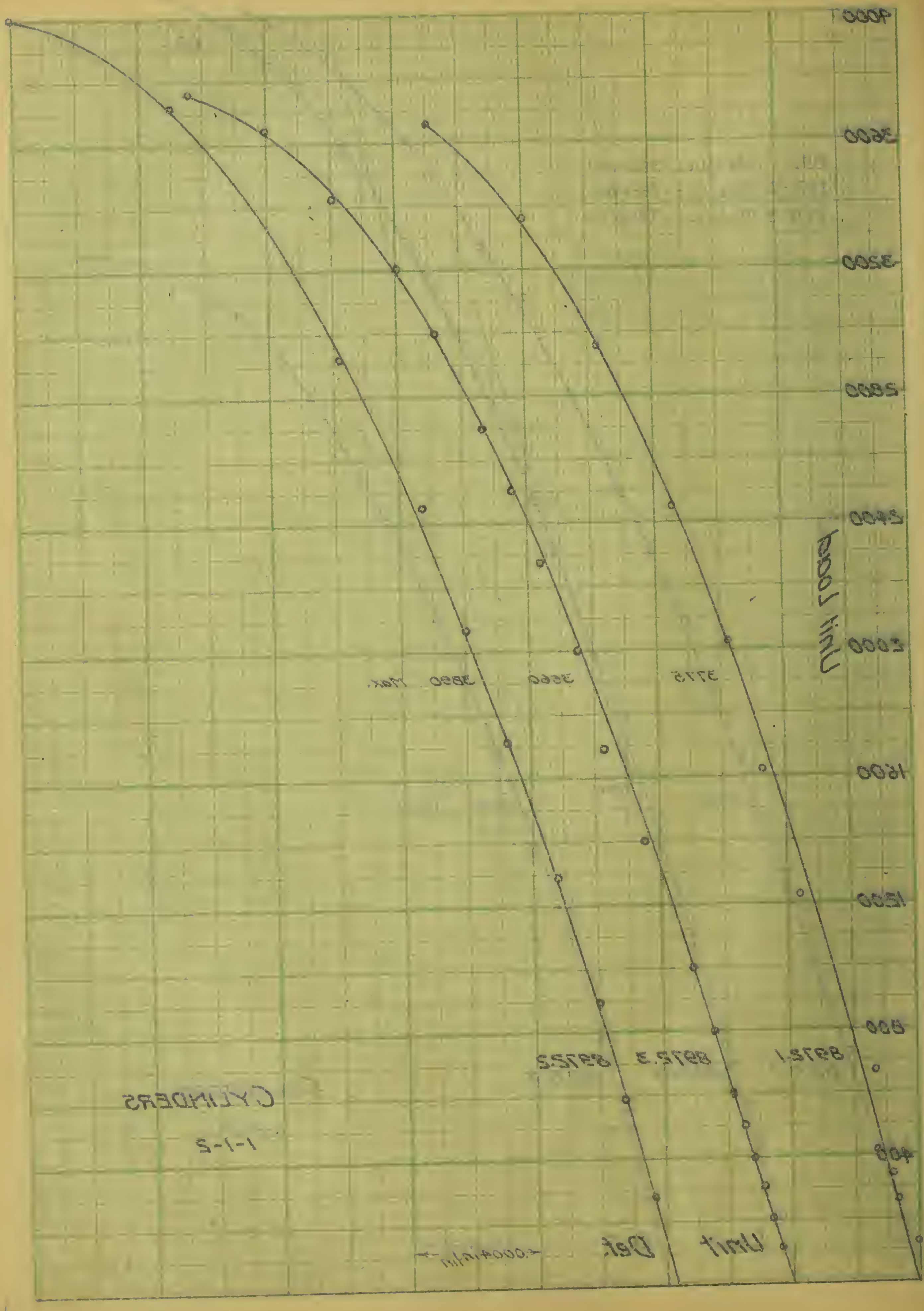

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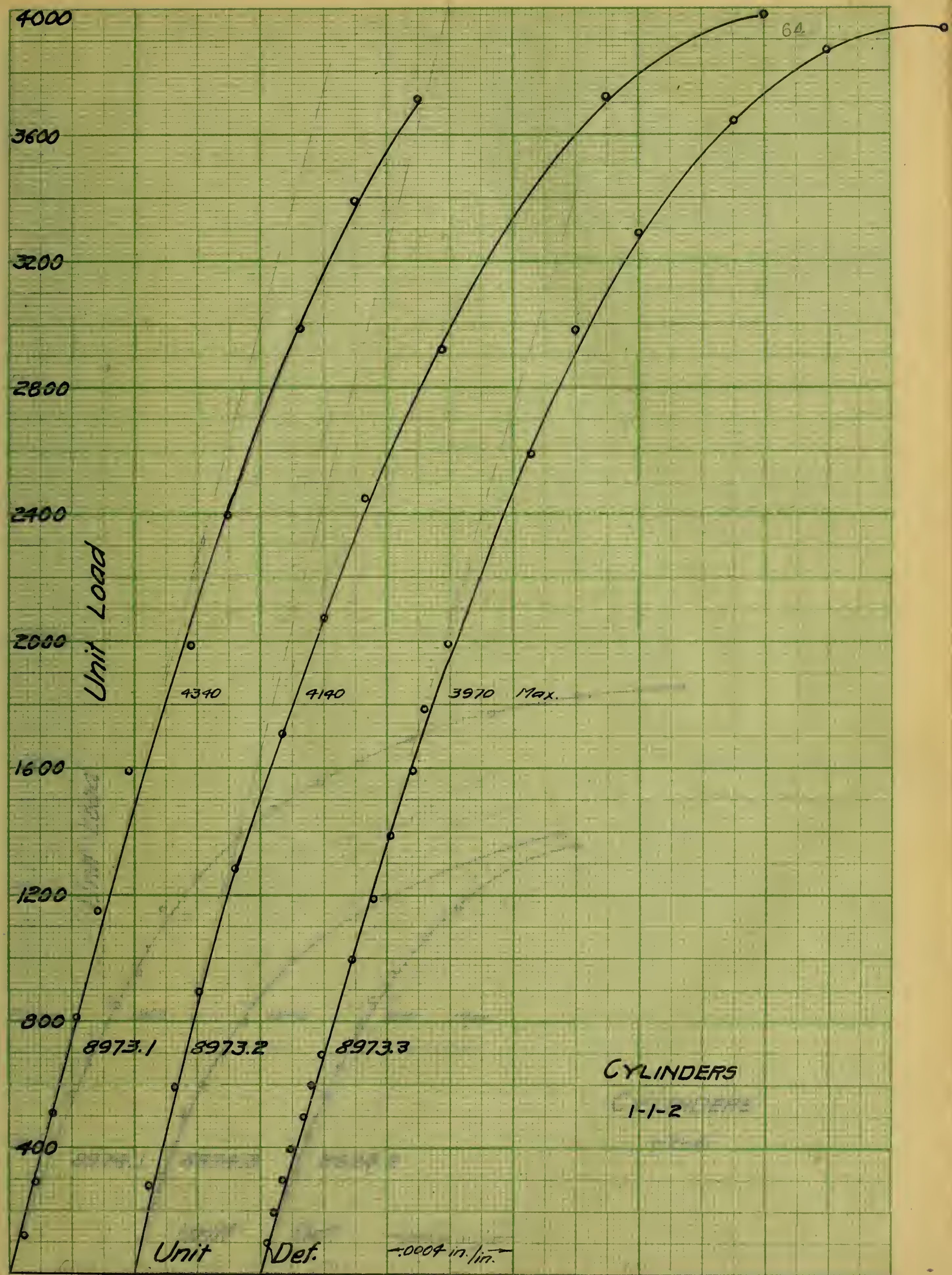

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Unit Load
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4140
3970
Max.
8973.1
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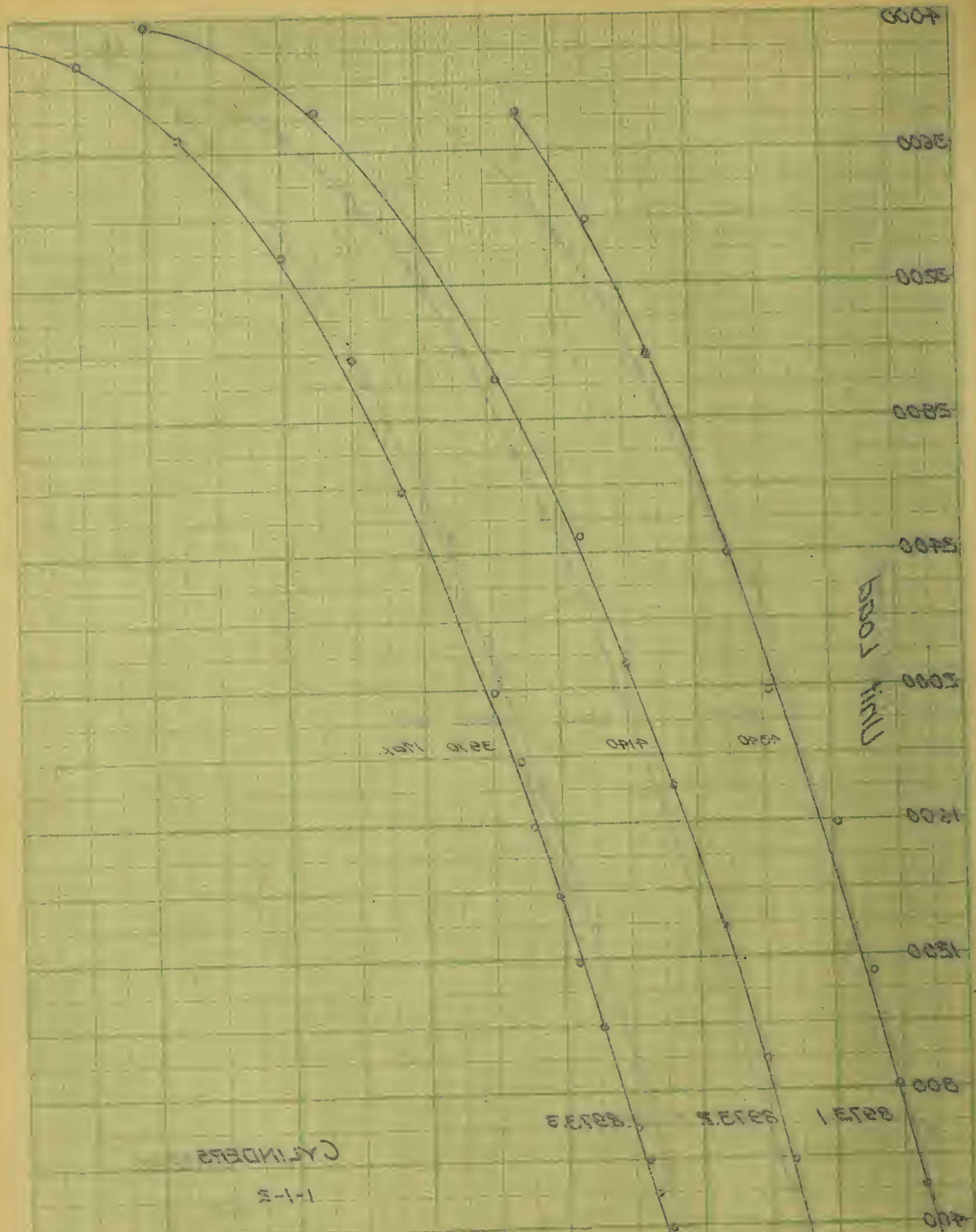
8973.3
CYLINDERS
1-1-2
Unit
Def.
.0004 in./in.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2800
2400
2000
1600
1200
800
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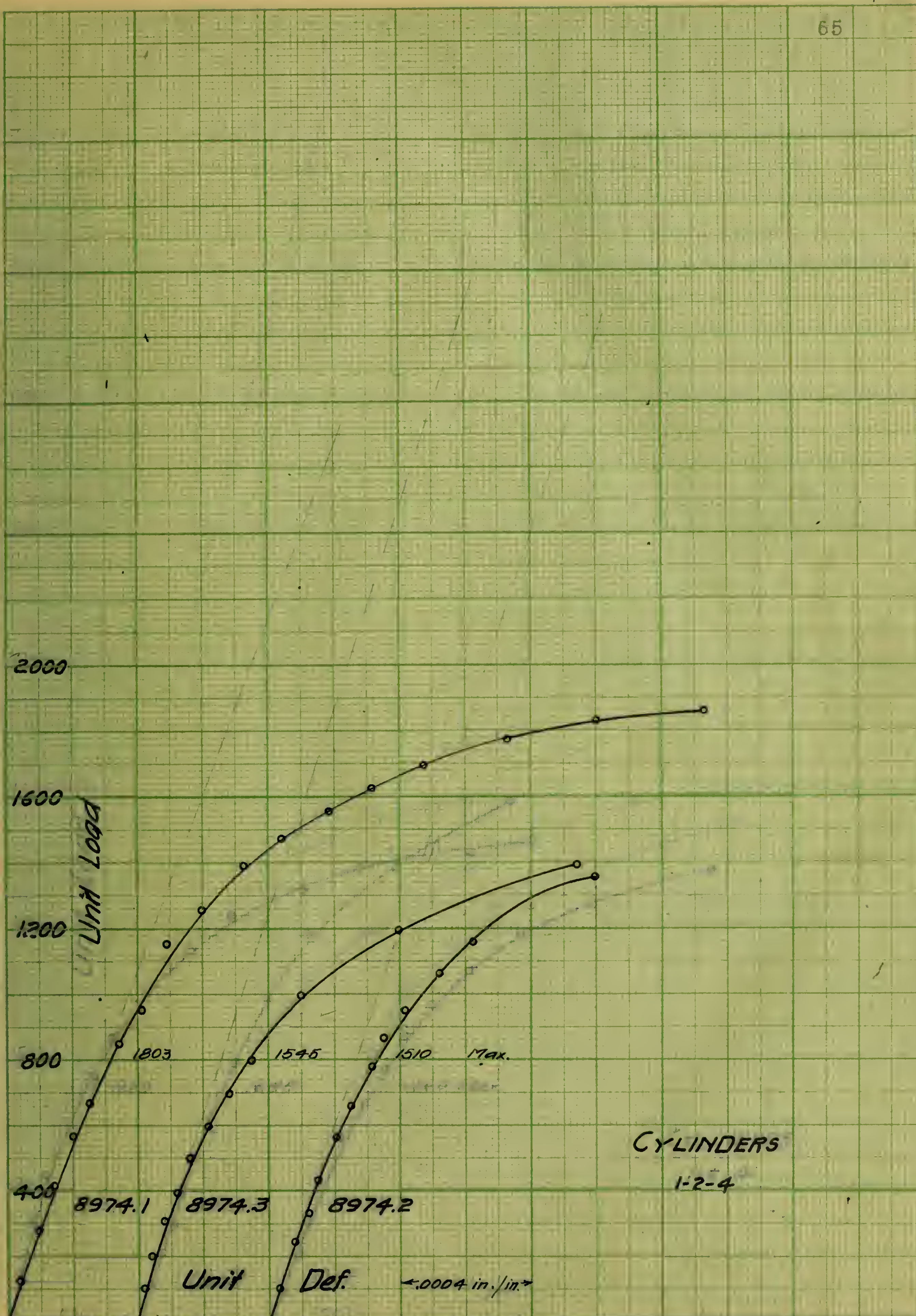
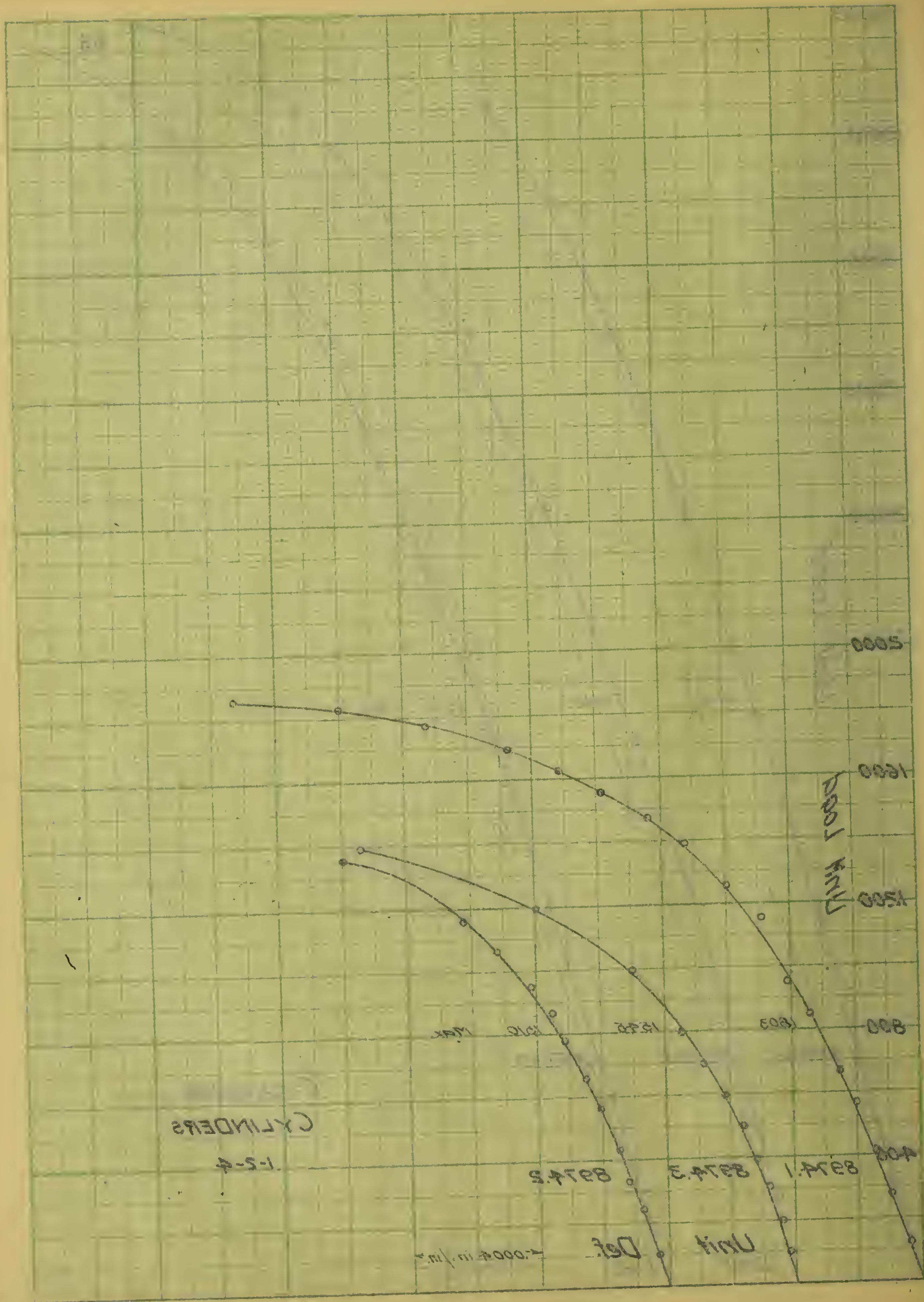
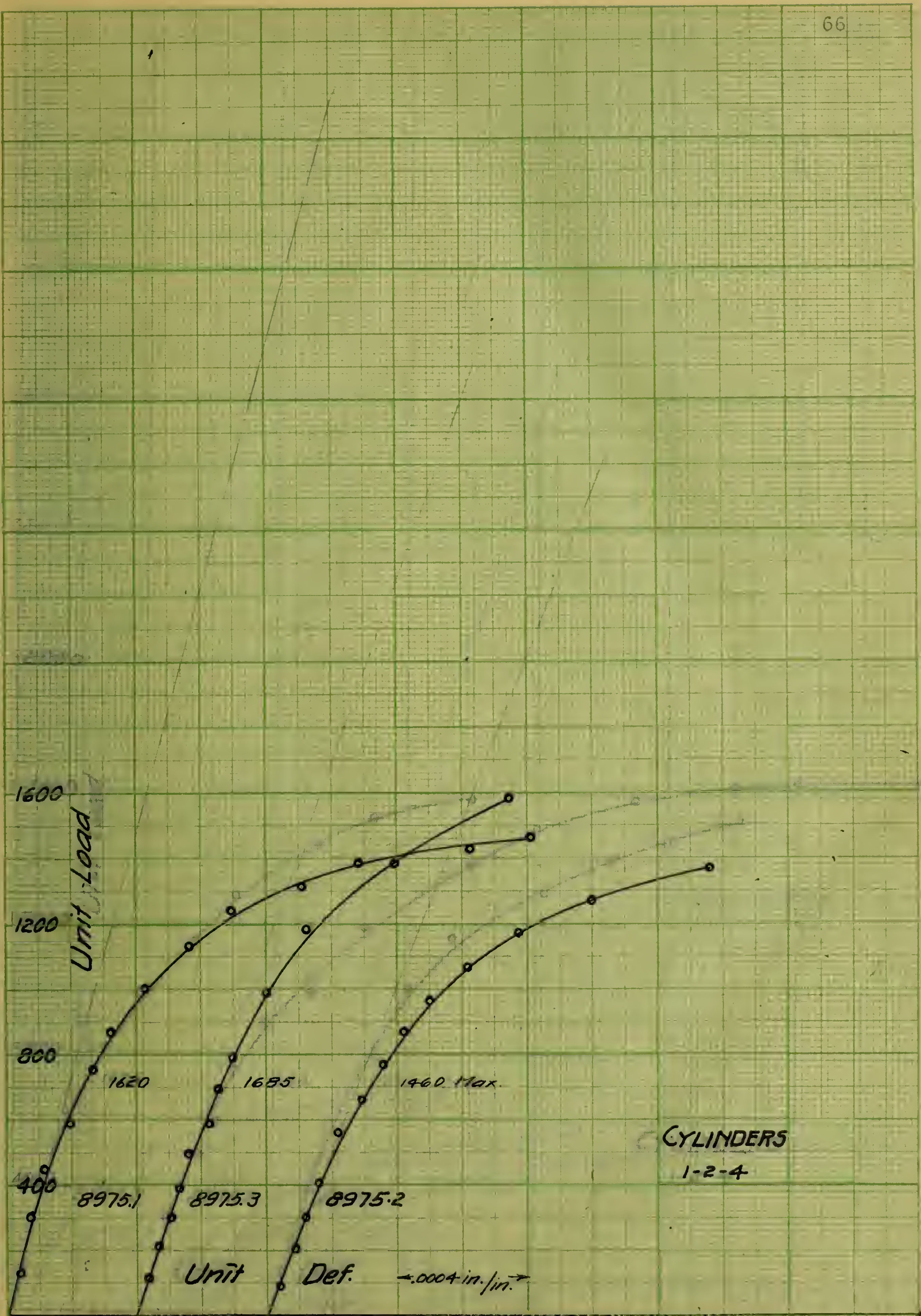
4140
3910 Max.
8973.1
8973.2
8973.3
CYLINDERS
1-1-2
Unit
Def.

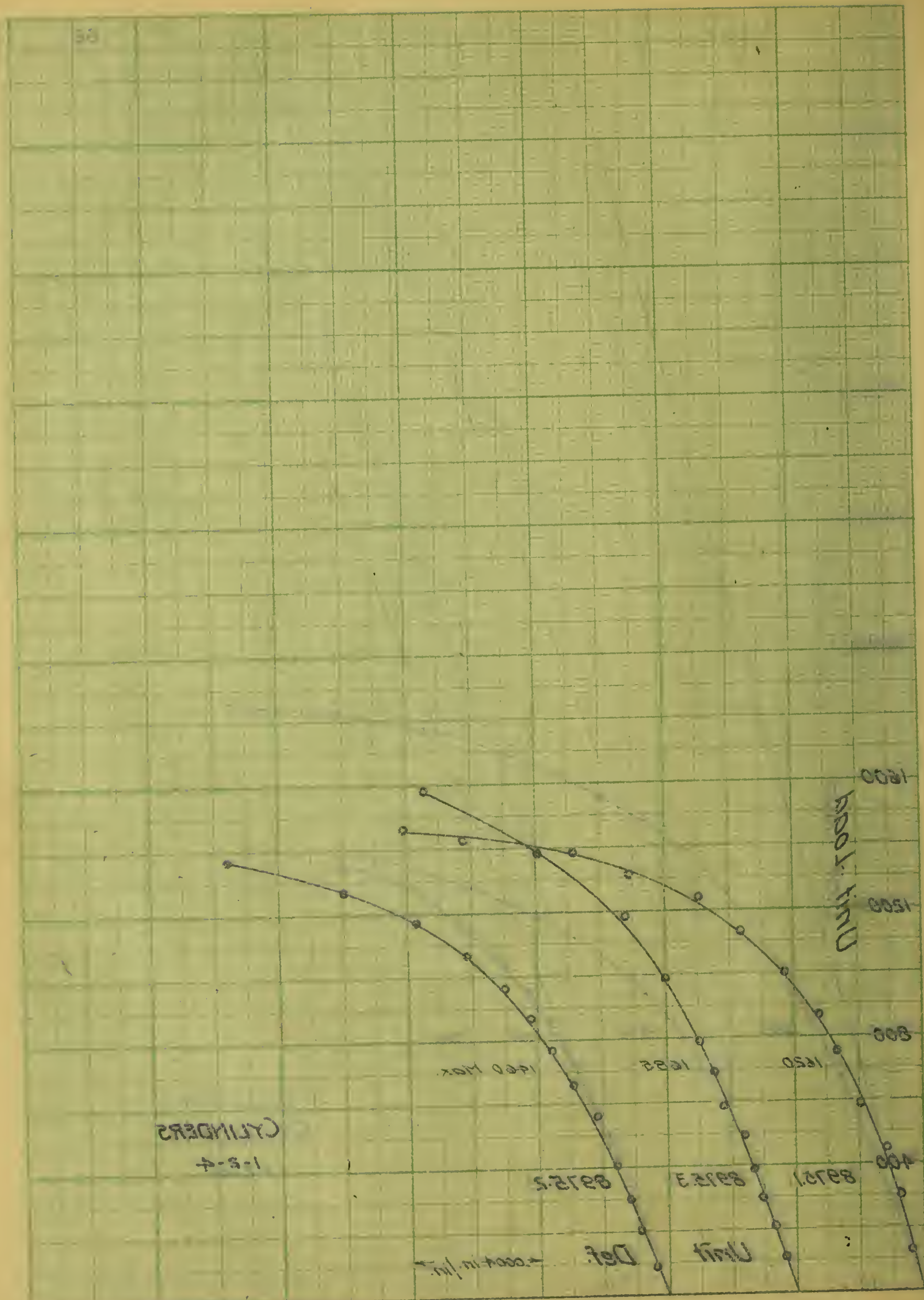

2000
1600
1200
800
400
Unit Load
1803
1545
1510
Max.
8974.1
8974.3
8974.2
Unit
Def.
.0004 in./in.
CYLINDERS
1-2-4



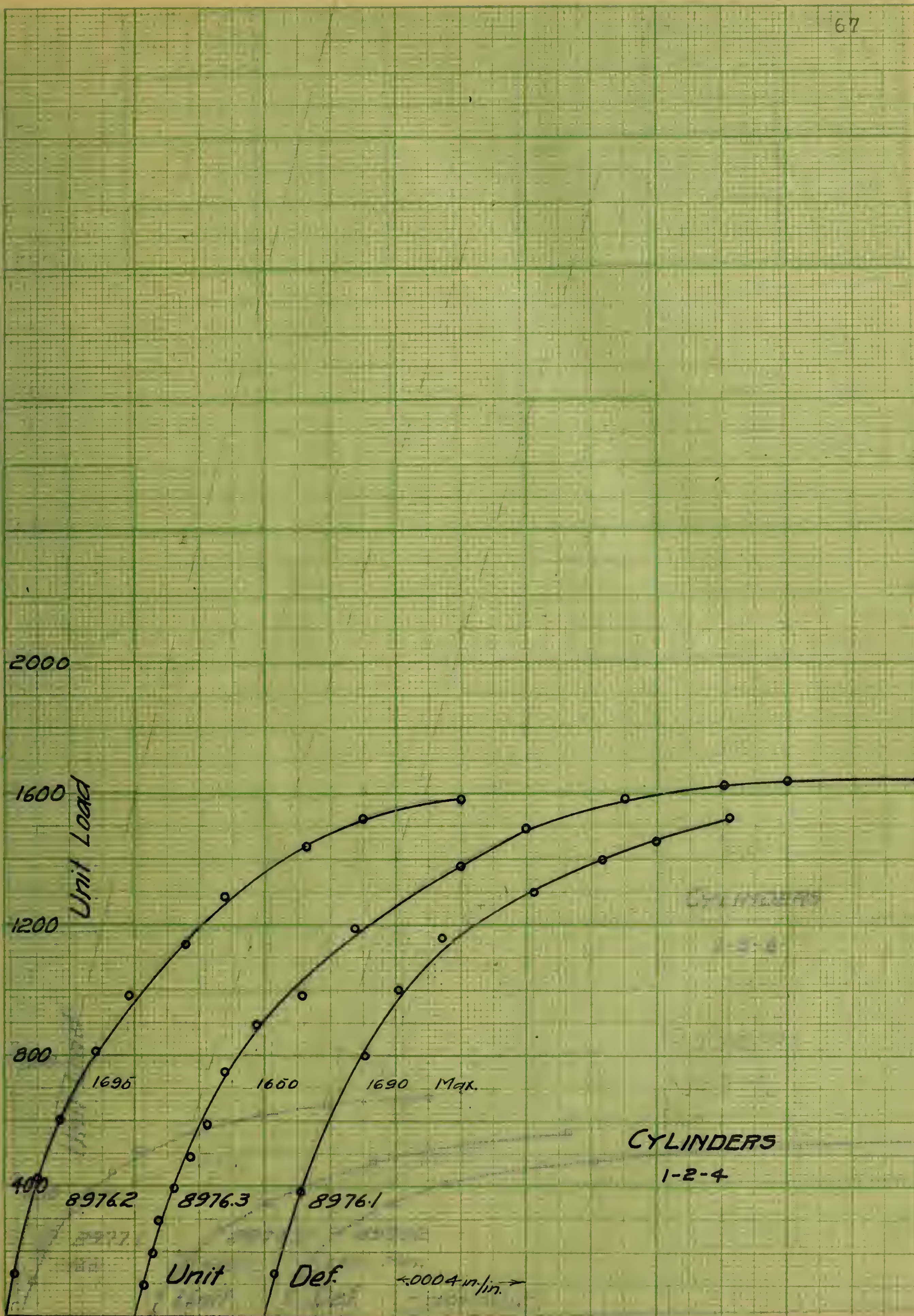
Unit Load
2000
1600
1200
800
400
CYLINDERS
1-2-4
8974.1
8974.3
8974.2
Unit Def.



1600
1200
800
400
Unit Load
1620
1685
1460 Max.
8975.1
8975.3
8975.2
Unit Def.
.0004 in./in.
CYLINDERS
1-2-4



Unit Load
1600
1200
800
400
1620
1685
1460 Max.
8975.1
8975.3
8975.2
CYLINDERS
1-2-4
Unit Def.
.0004 in./in.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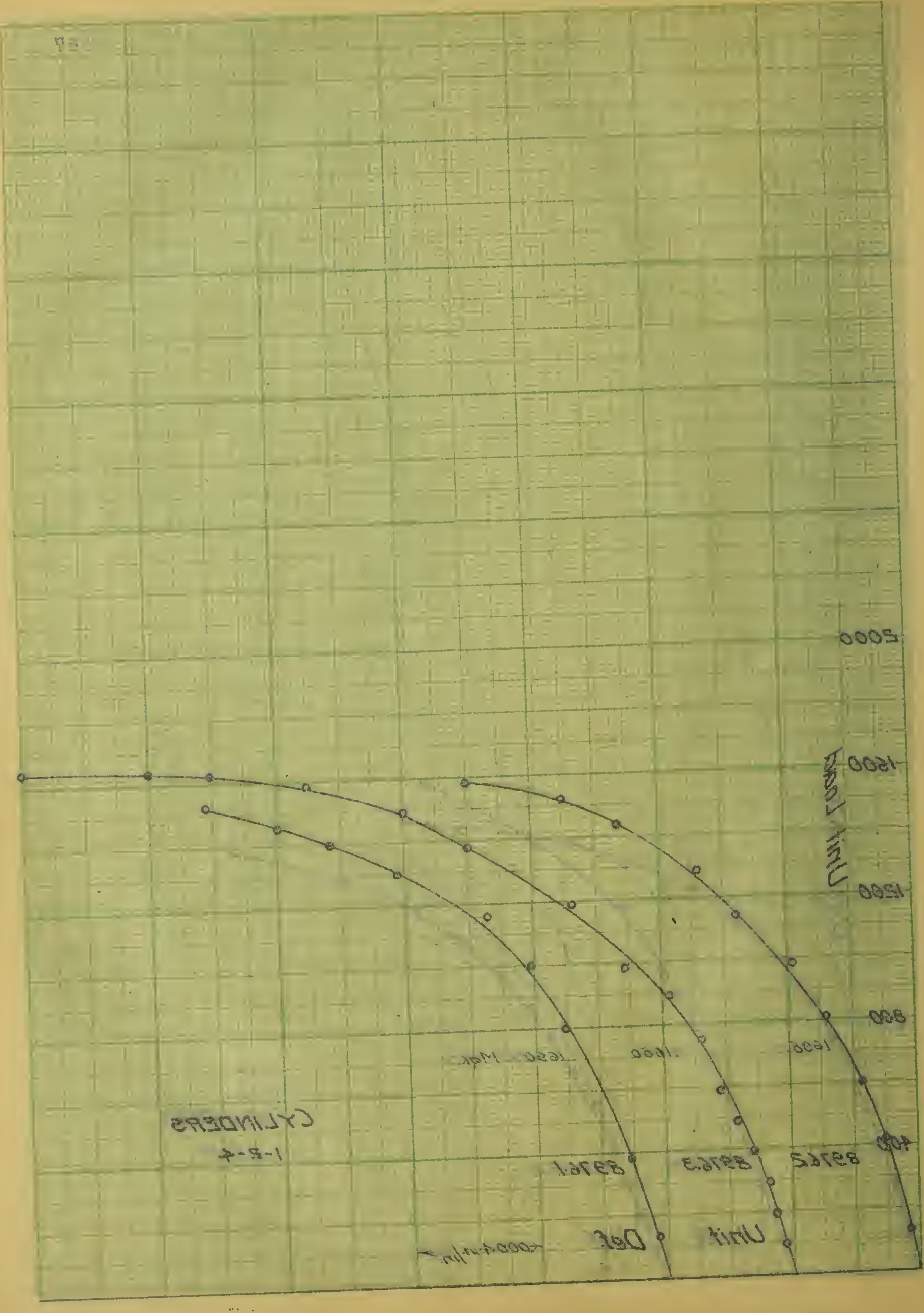
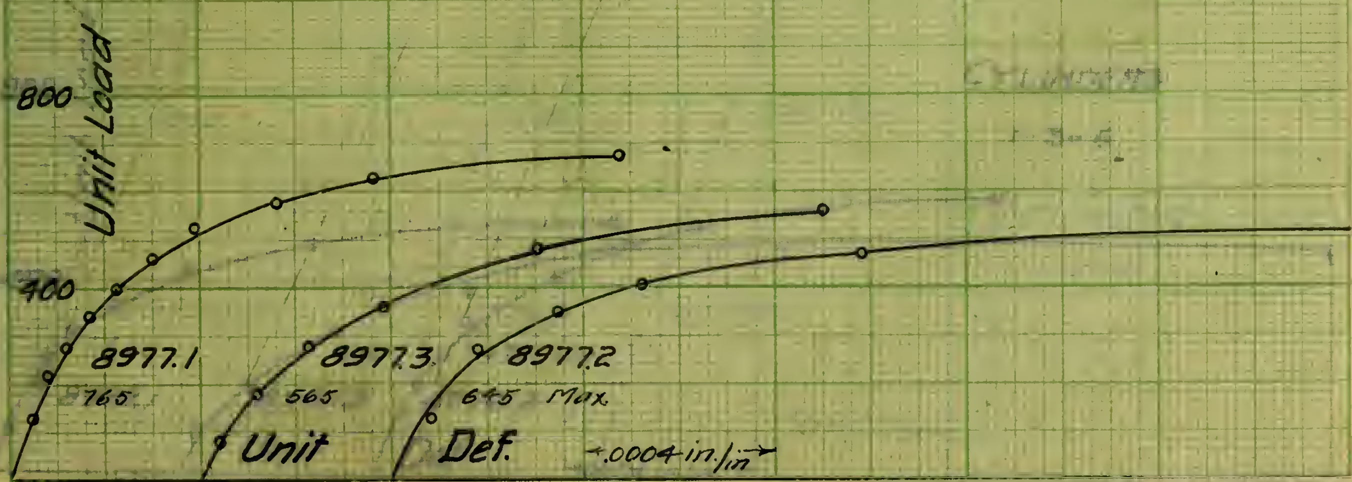
1600
1200
800
400
Unit Load
1695
1650
1690
Max.
8976.2
8976.3
8976.1
Unit
Def.
.0004 in./in.
CYLINDERS
1-2-4

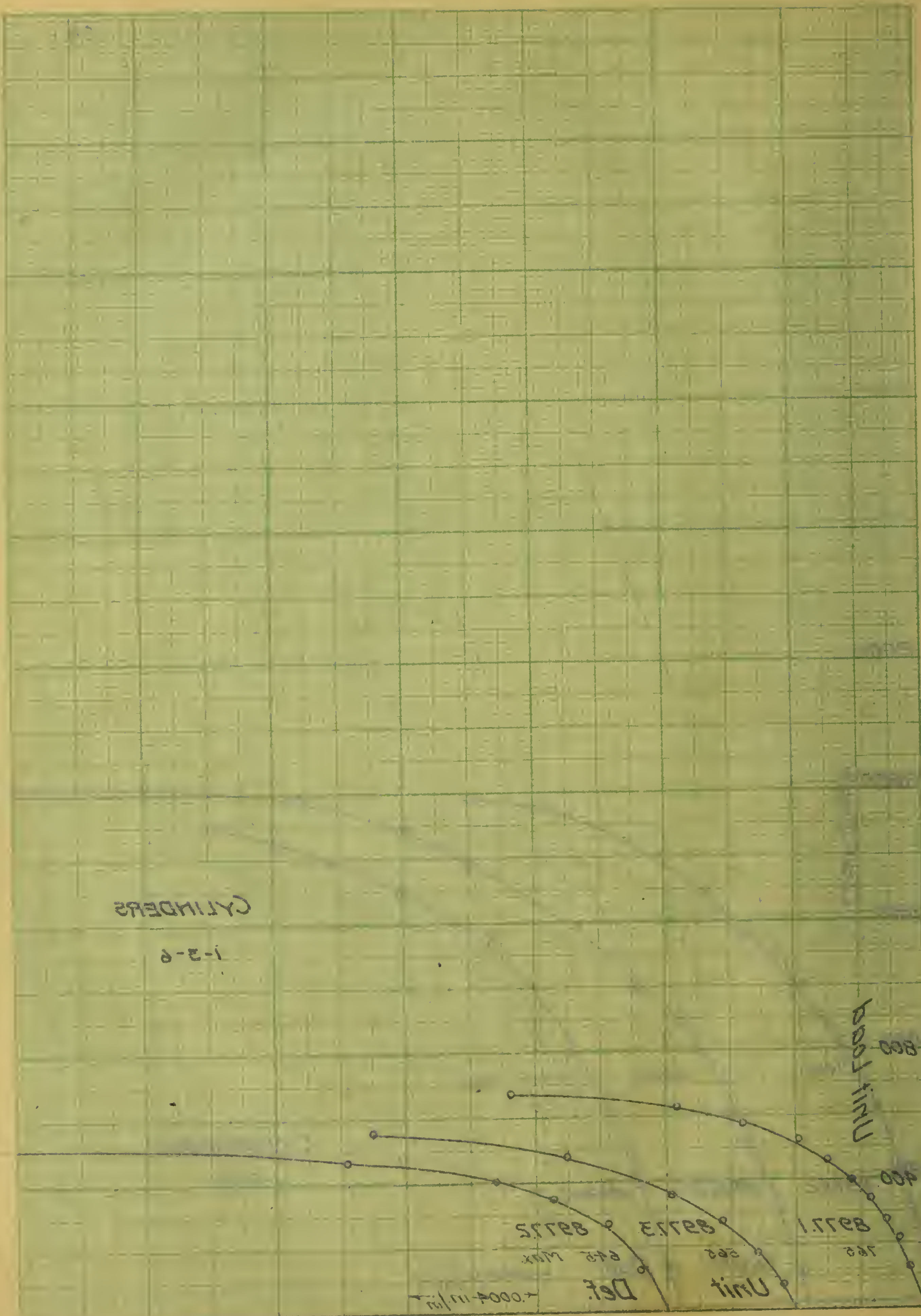


CYLINDERS
1-2-4
8976.1
8976.3
8976.2
Unit Def.
Unit Load
2000
1600
1200
800
400
1650 Max.
1650
1650

CYLINDERS

1-3-6





CYLINDERS
1-3-6
Unit Load
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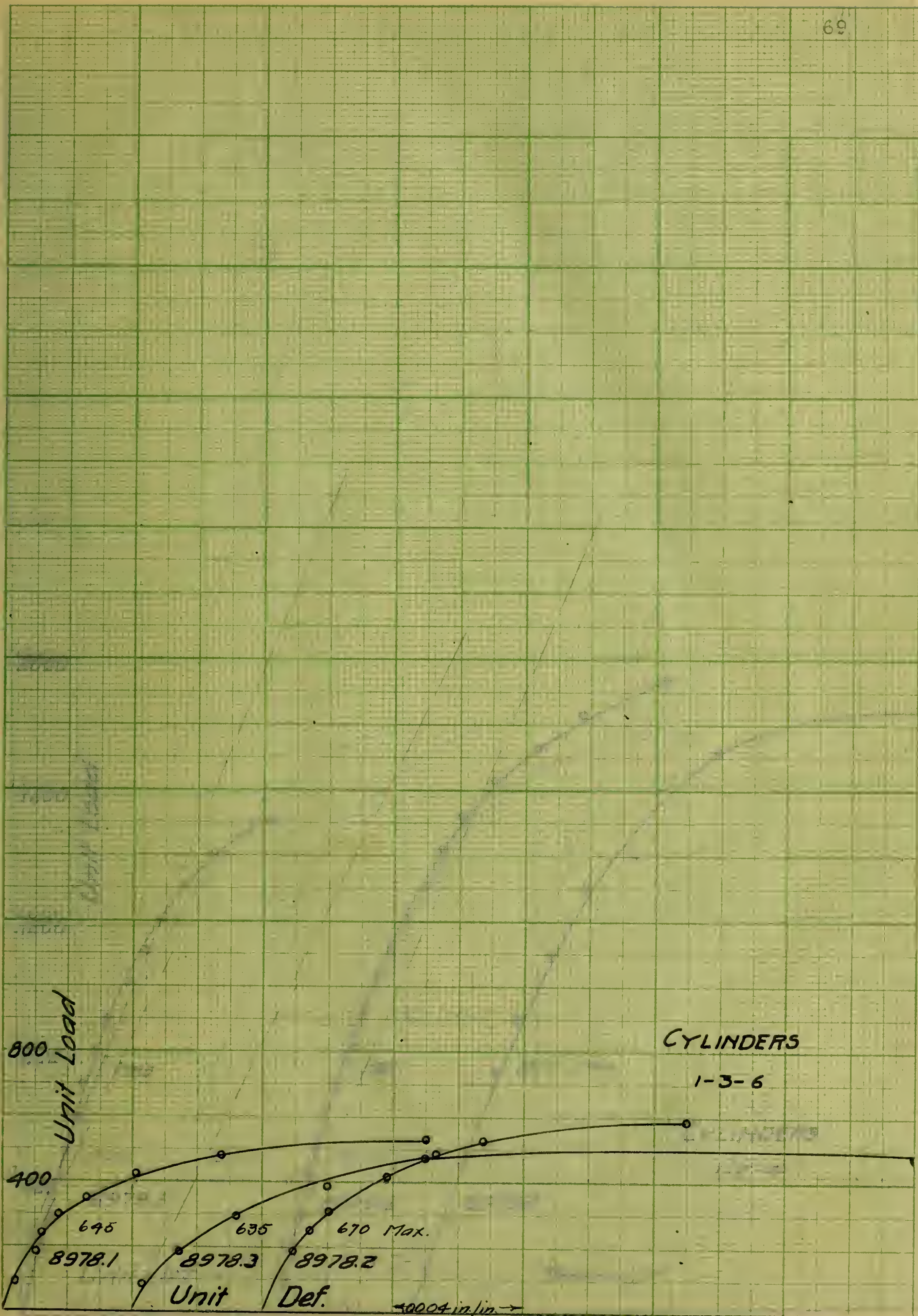
400
8977.1
765
8977.3
566
8977.2
646 Max.
Unit
Def.
.0004 in/in


Unit Load
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400
CYLINDERS
1-3-6
645
635
670 Max.
8978.1
8978.3
8978.2
Unit Def.
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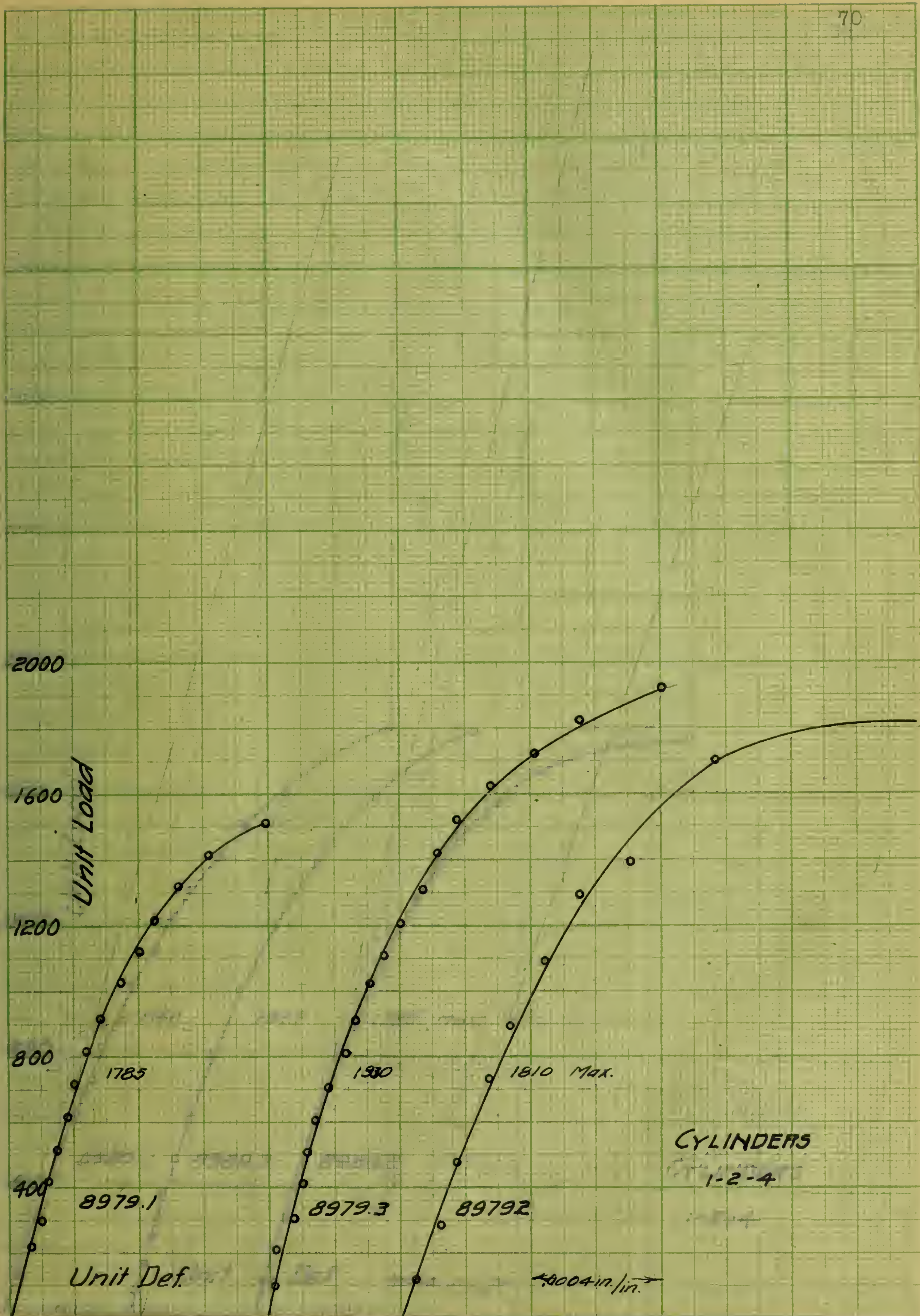
2000
1600
1200
800
400
Unit Load
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1930
1810 Max.
8979.1
8979.3
89792
Unit Def.
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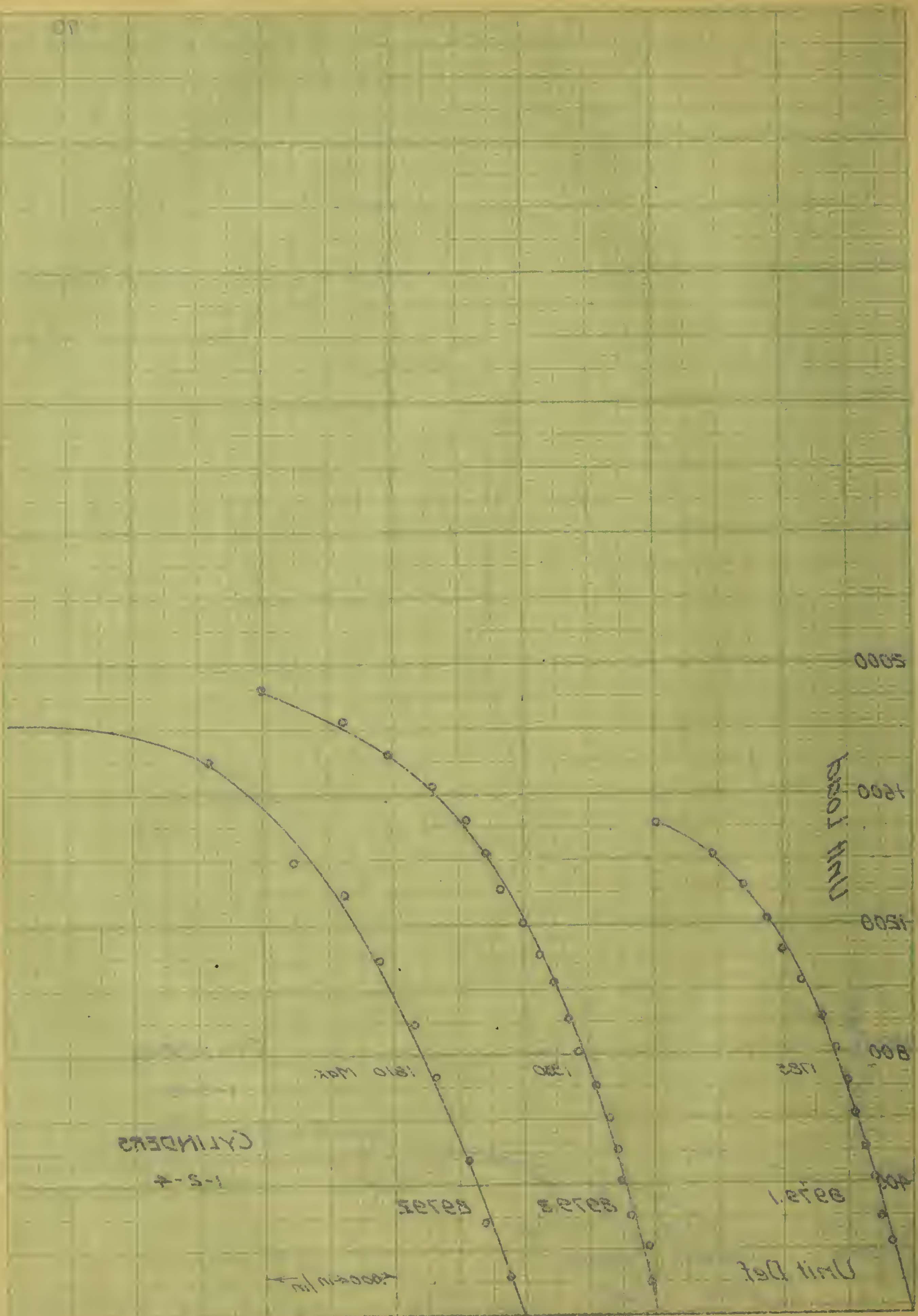
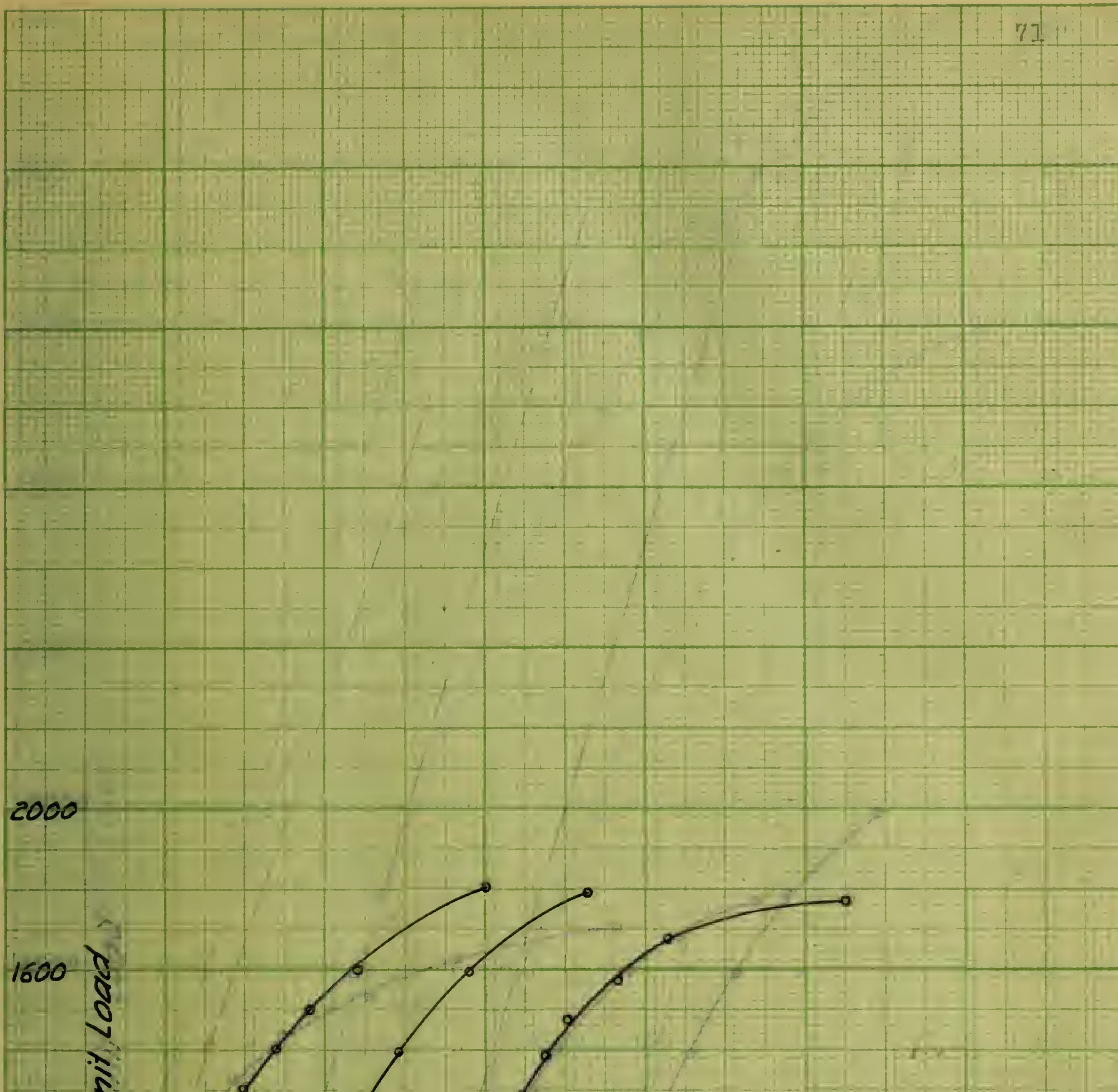
CYLINDERS
1-2-4



70
CYLINDERS
1-2-4
Unit Load
Unit Def
2000
1600
1200
800
400
8979.1
8979.2
8979.3
1810 Max.
1330
1785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400
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1925
1720 Max.
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Unit Def.
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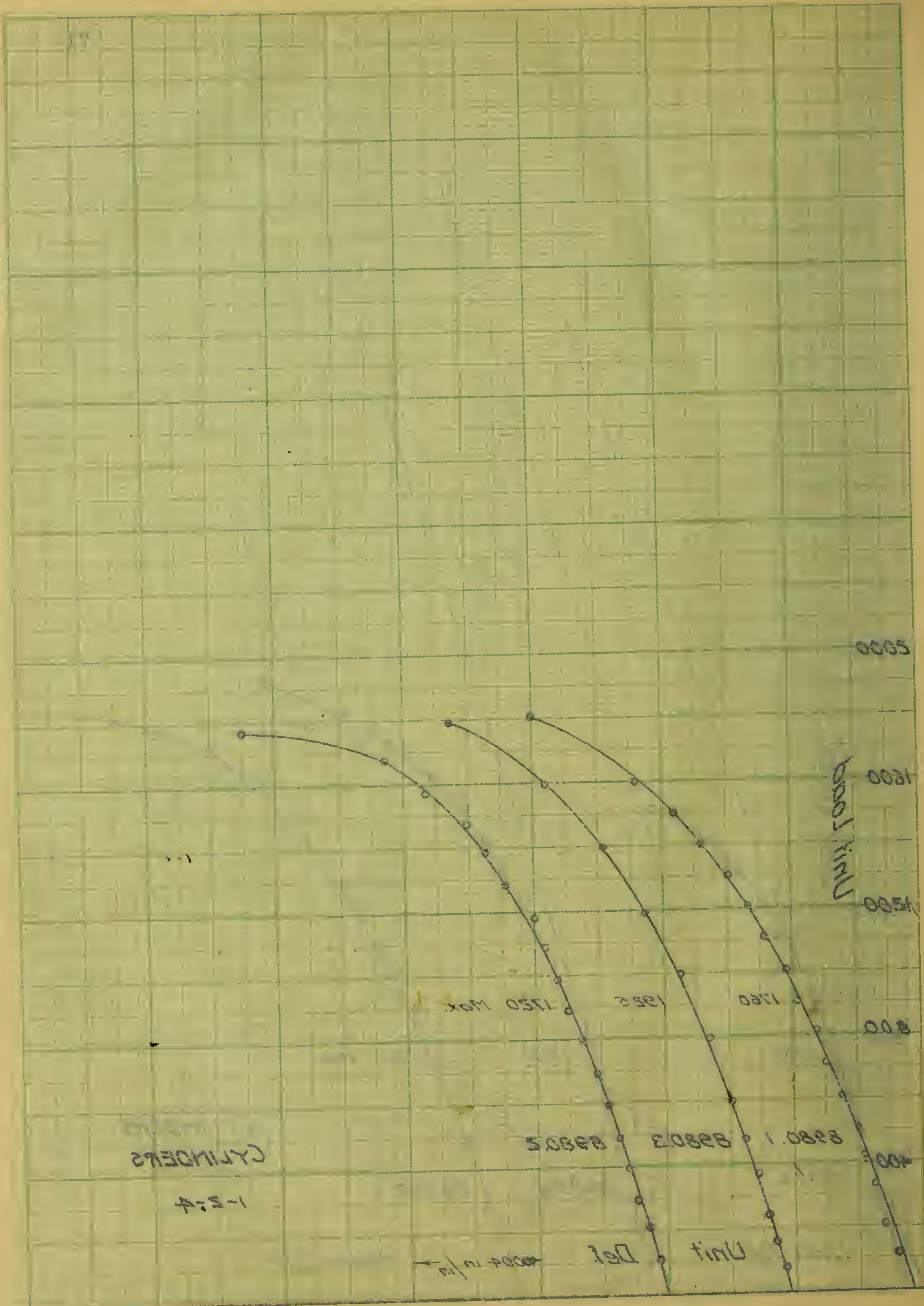
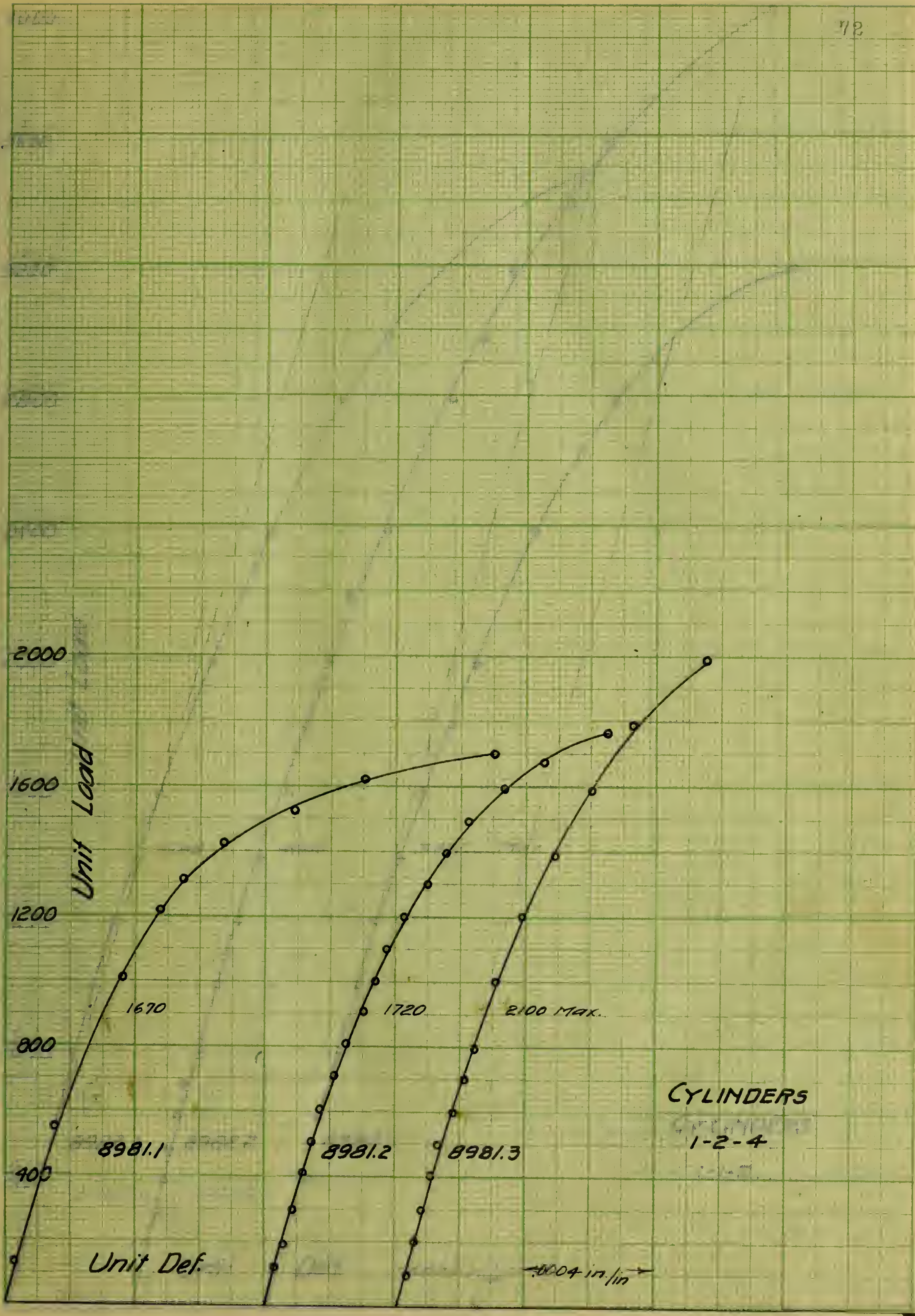
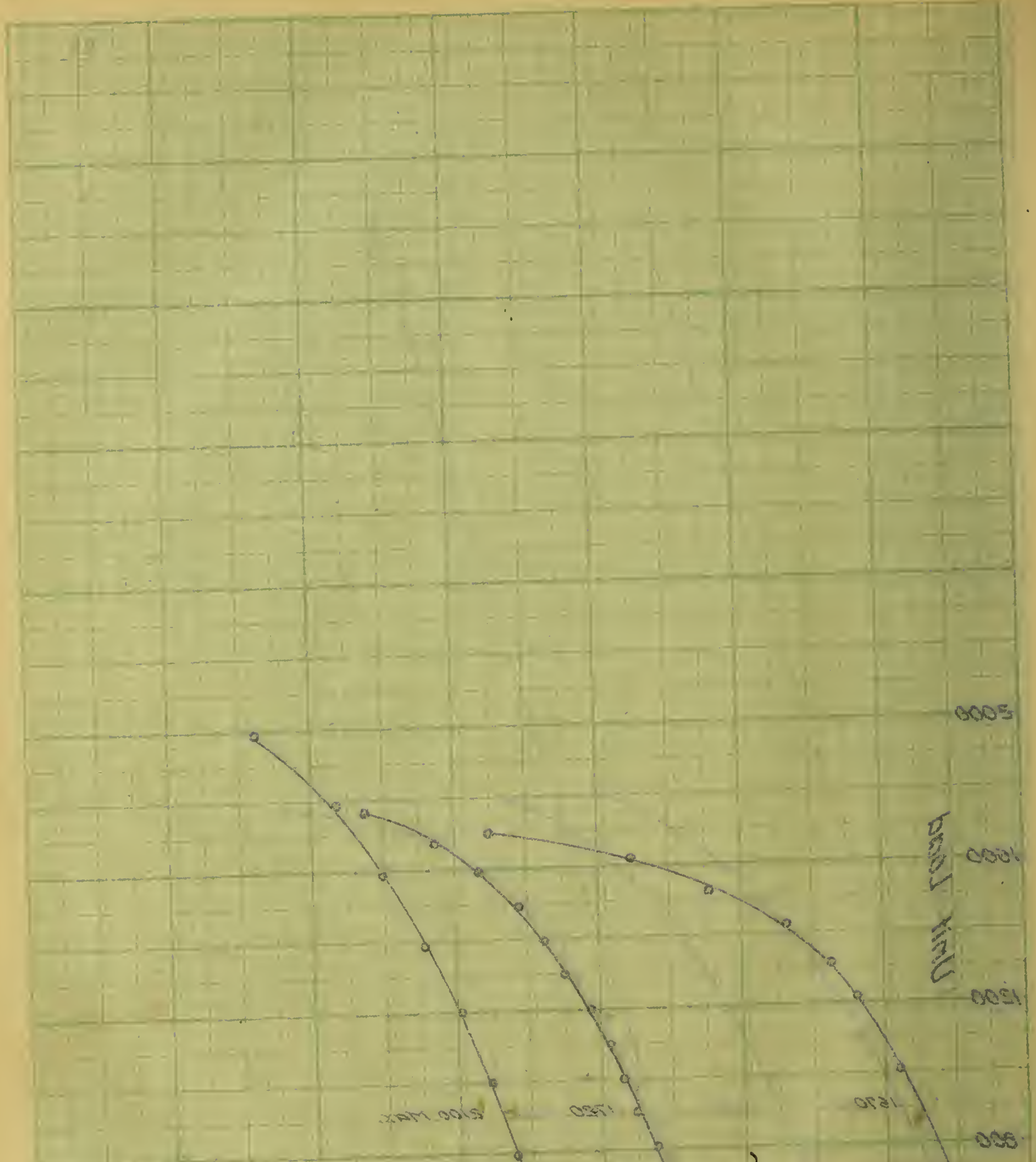
CYLINDERS
1-2-4



CYLINDERS
1-2-4
Unit Load
2000
1600
1200
800
400
1760
1925
1720 Max.
6980.1
6980.3
6982.2
Unit Def
.0004 in/in



2000
1600
1200
800
400
Unit Load
Unit Def.
.0004 in./in
1670
1720
2100 Max.
8981.1
8981.2
8981.3
CYLINDERS
1-2-4



Unit Load
Unit Def.
CYLINDERS
1-2-4
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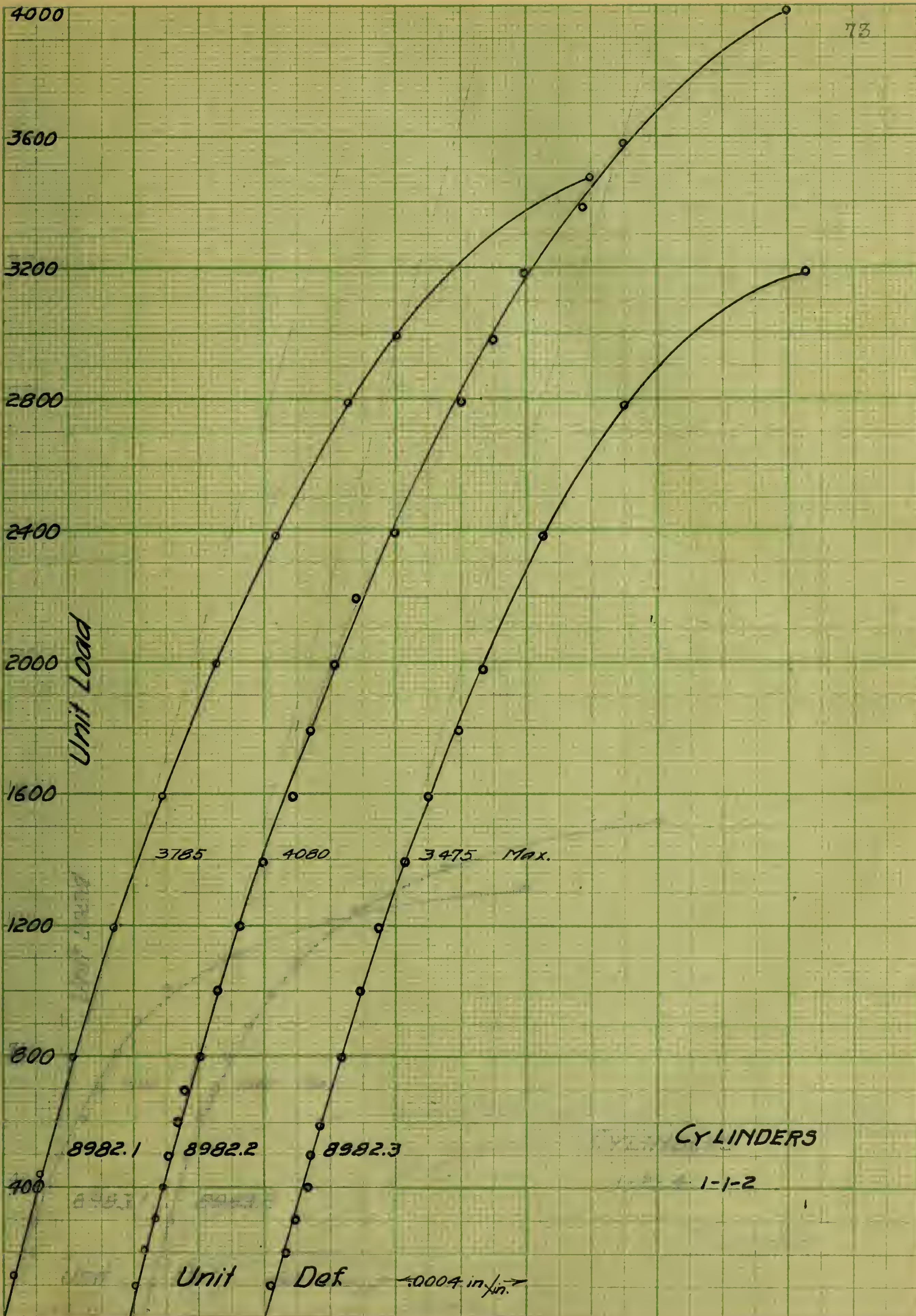
6981.2
6981.3
1670
1720
2100 Max.
.0004 in/in
400
800
1200
1600
2000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1600
1200
800
400
Unit Load
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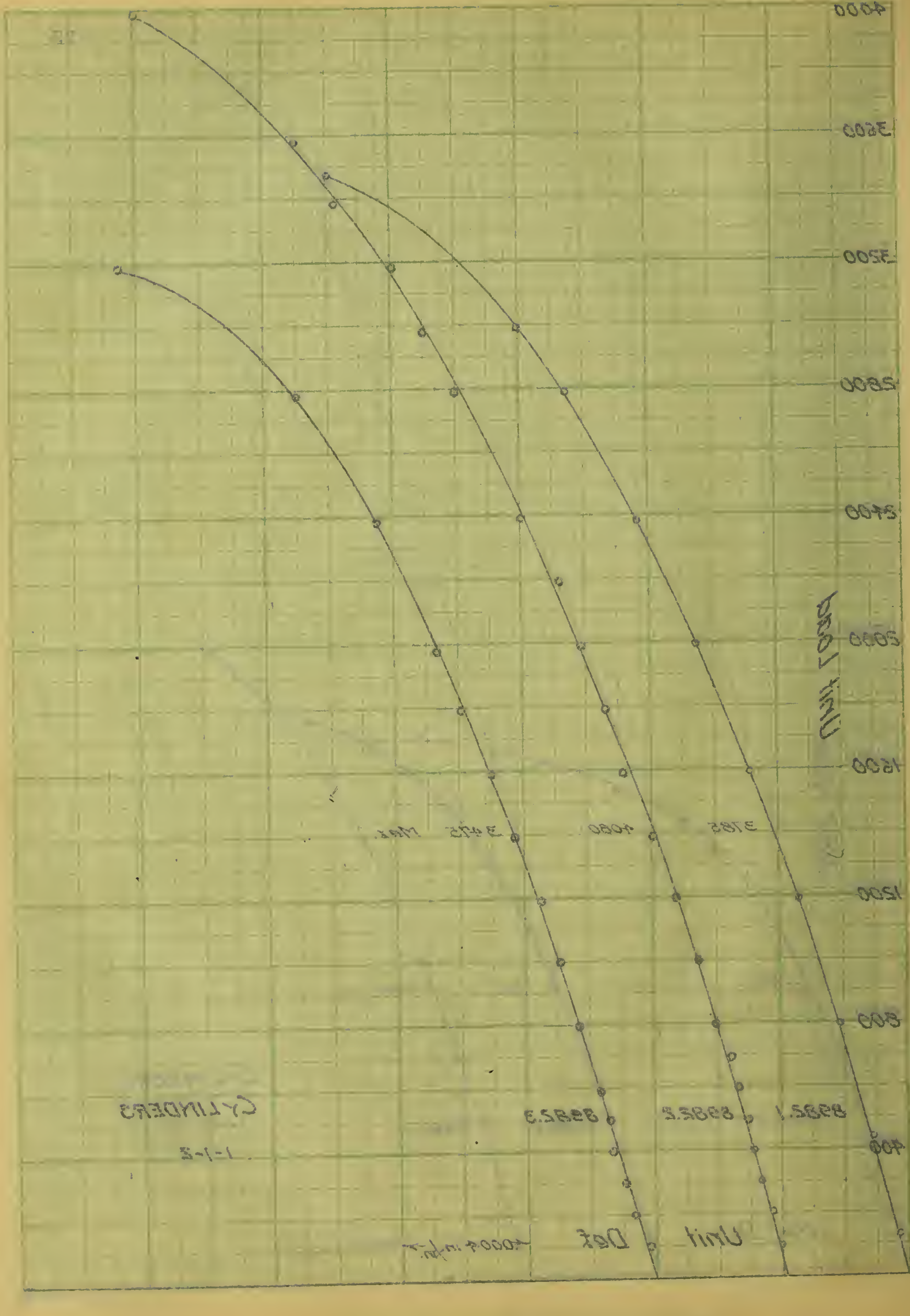
4080
3.475
Max.
8982.1
8982.2
8982.3
CYLINDERS
1-1-2
Unit
Def.
.0004 in/in.



Unit Load
Unit Def .0004 in./in.
CYLINDERS
1-1-2
3785
4080
3475 Max.
400
800
1200
1600
2000
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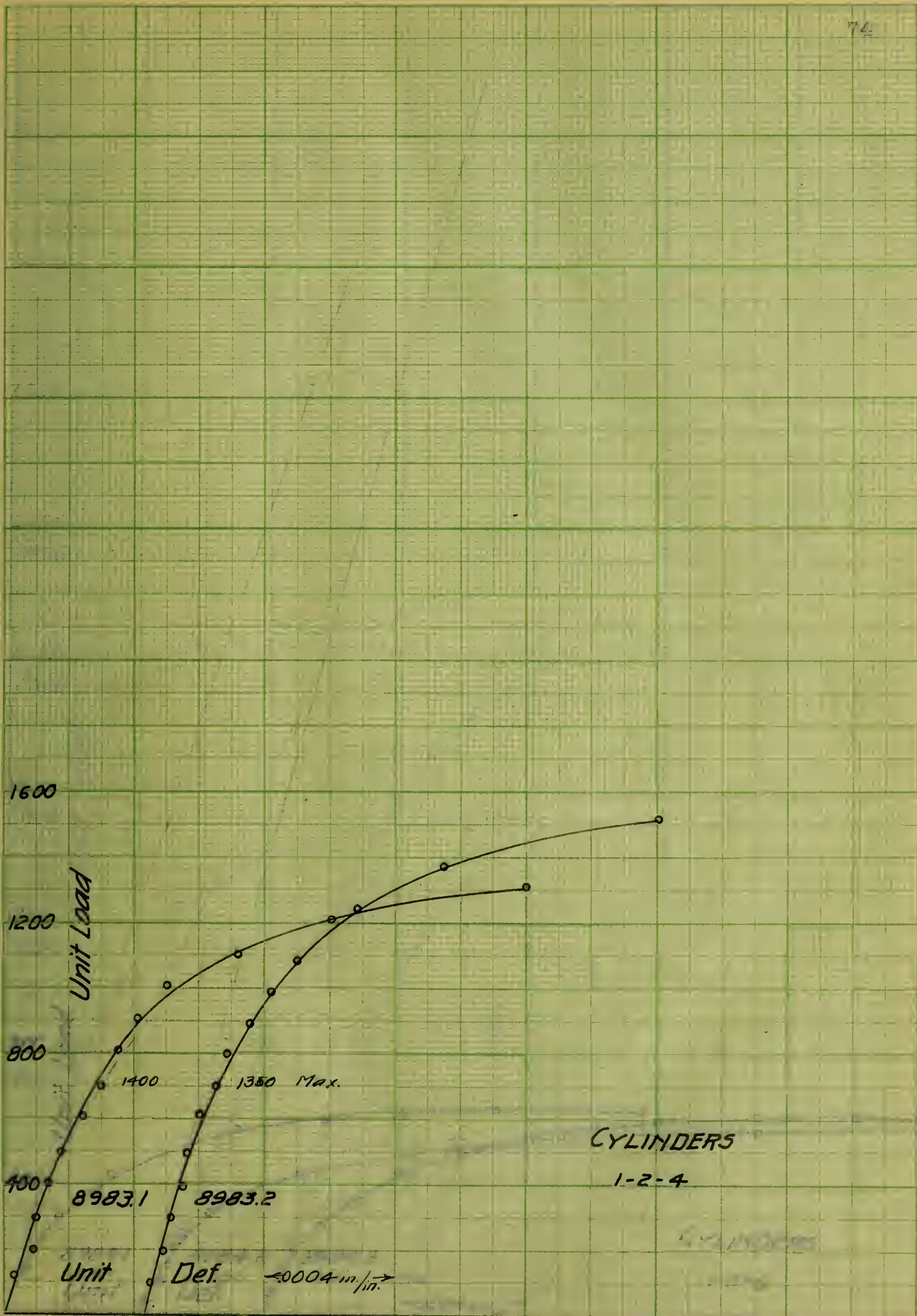
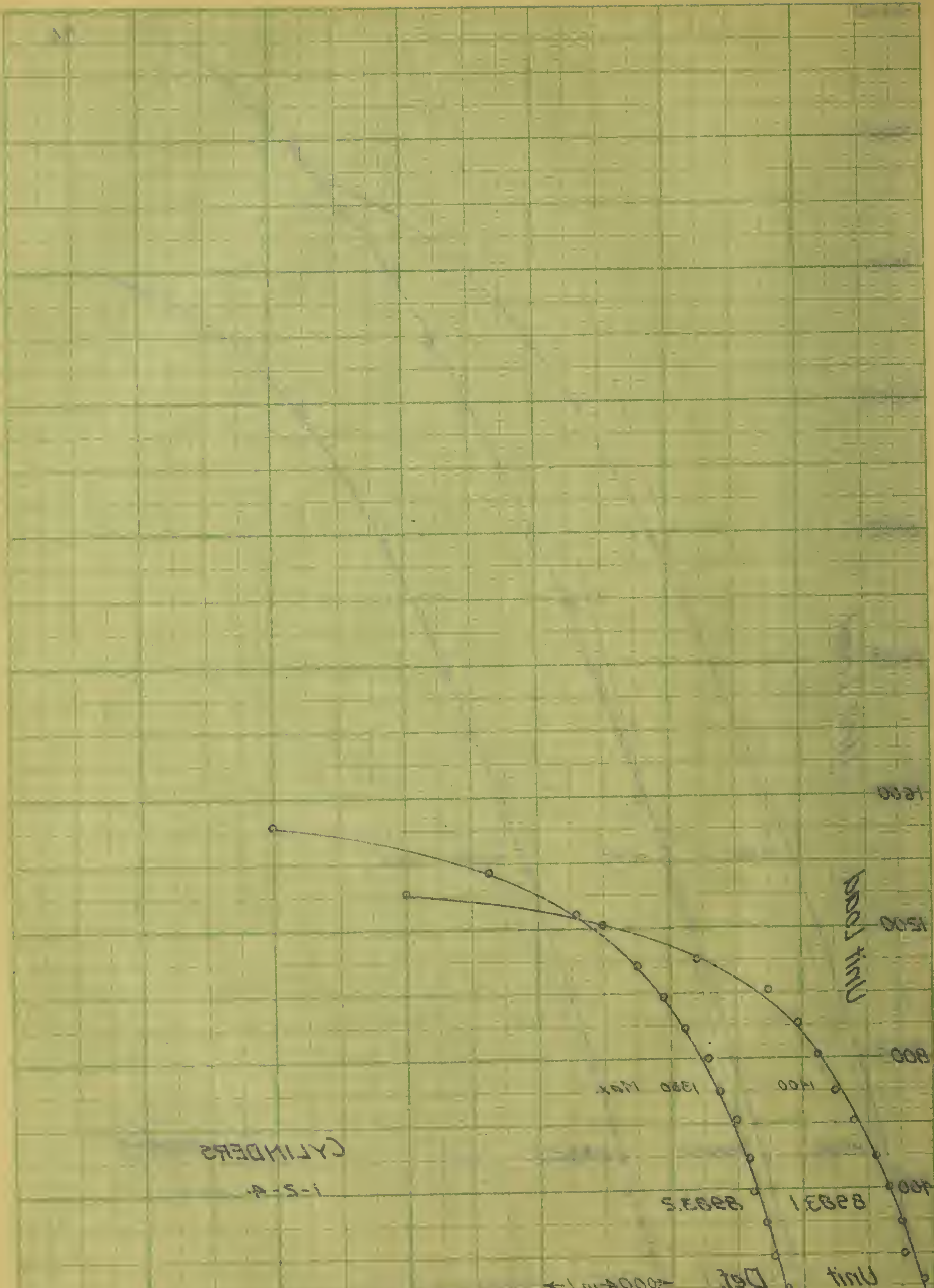
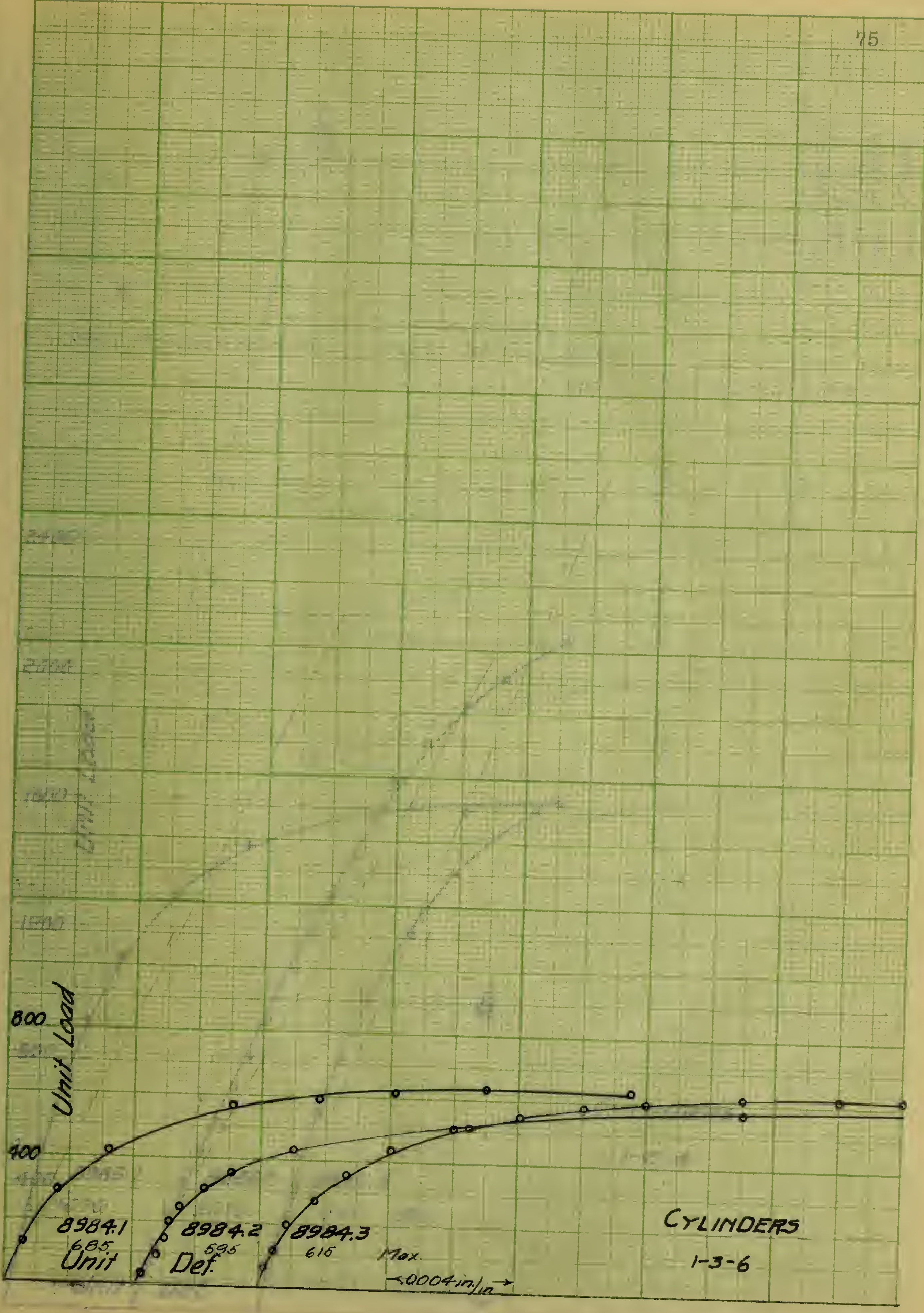
2800
3200
3600
4000


1600
1200
800
400
Unit Load
1400
1350 Max.
8983.1
8983.2
Unit Def. ←.0004 in./in.→
CYLINDERS
1-2-4



CYLINDERS
1-2-4
8983.1
8983.2
Unit Load
Unit Def. .0004 in/in.
400
800
1200
1600
1400
1330 Max.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Unit Load
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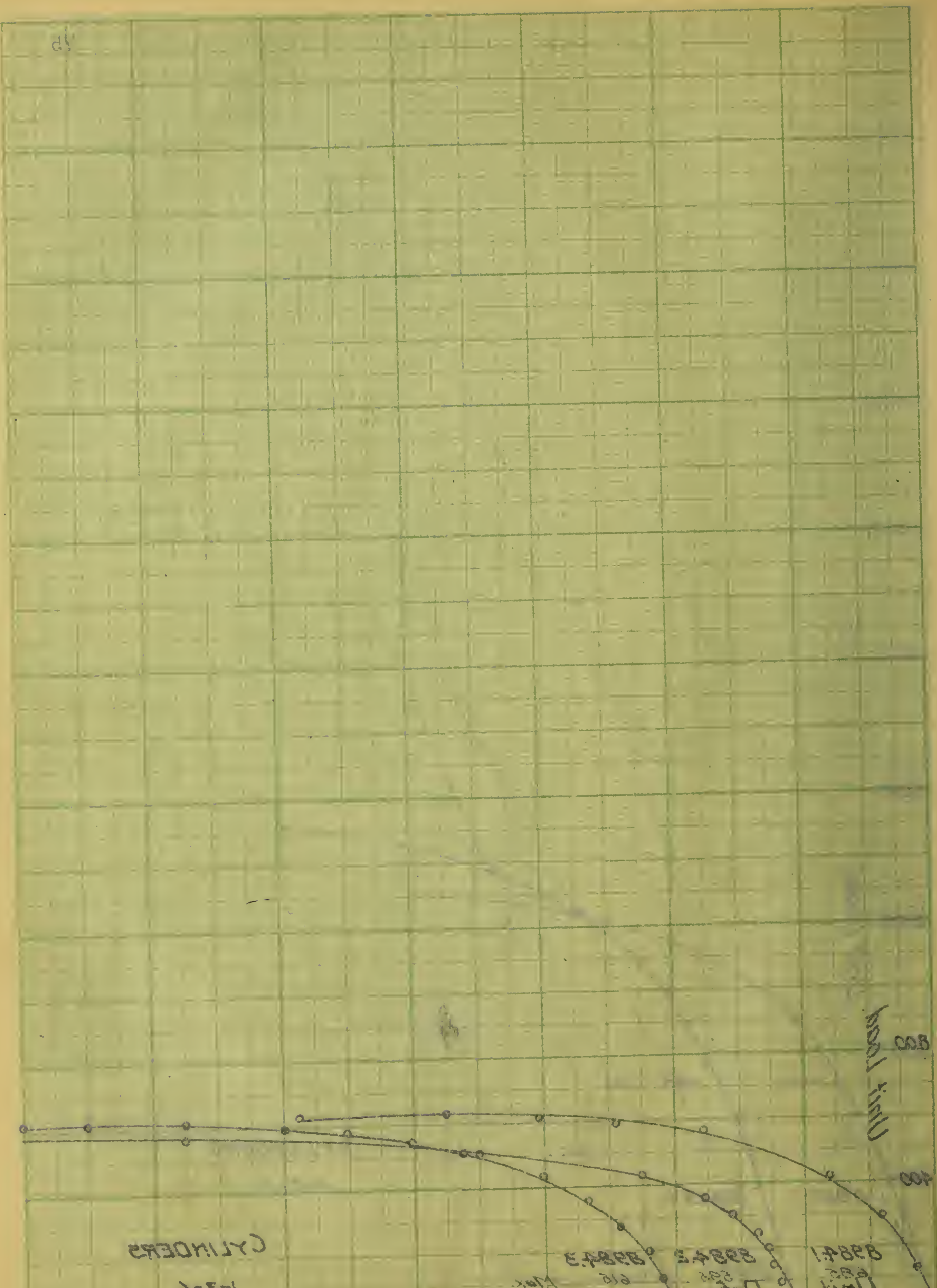
685
Unit
8984.2
595
Def.
8984.3
616
Max.
.0004 in/in
CYLINDERS
1-3-6


CYLINDERS
1-3-6
Unit Load
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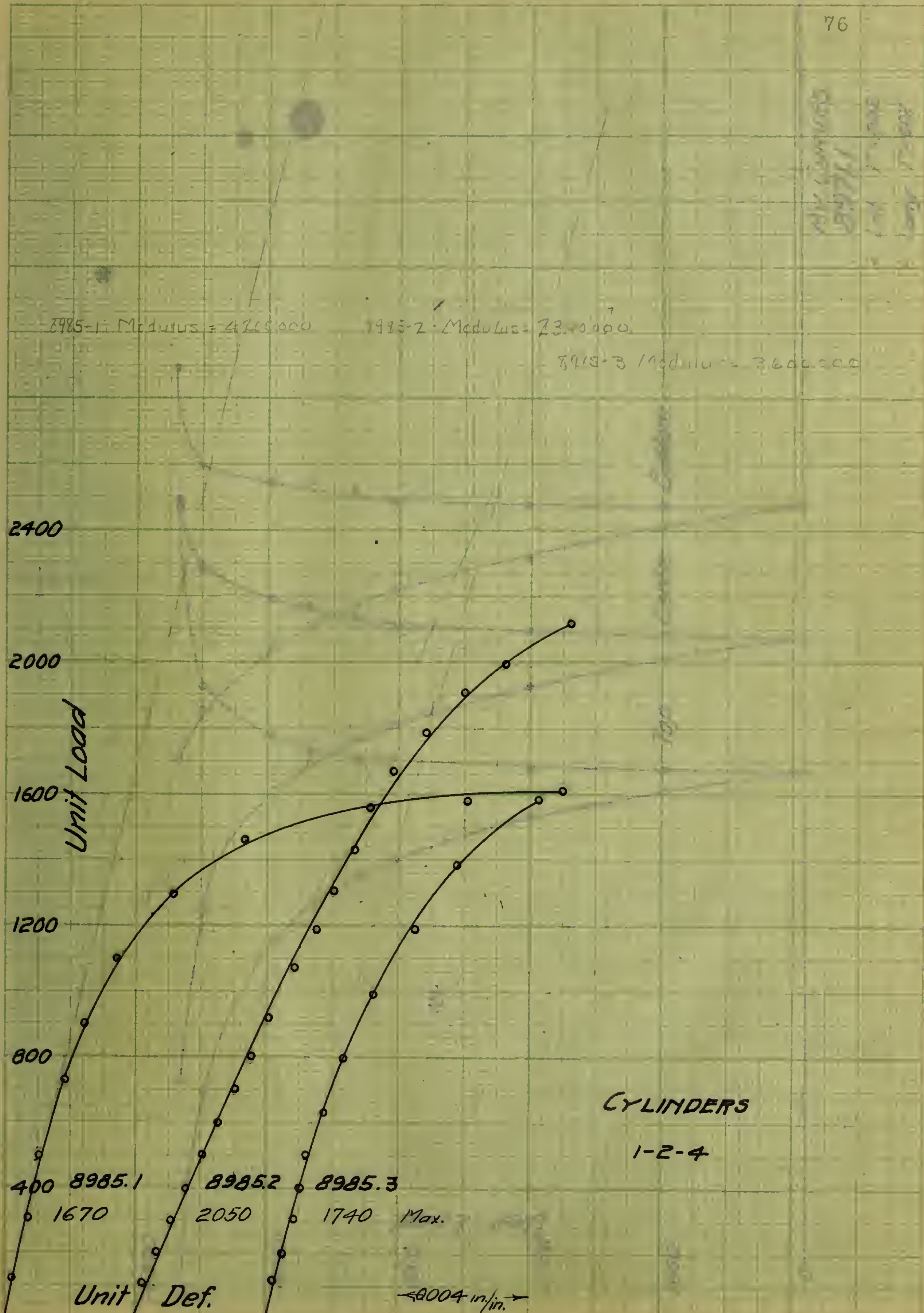
800
8984.1
8984.2
8984.3
Unit Def.
Max.


2400
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1200
800
400
Unit Load
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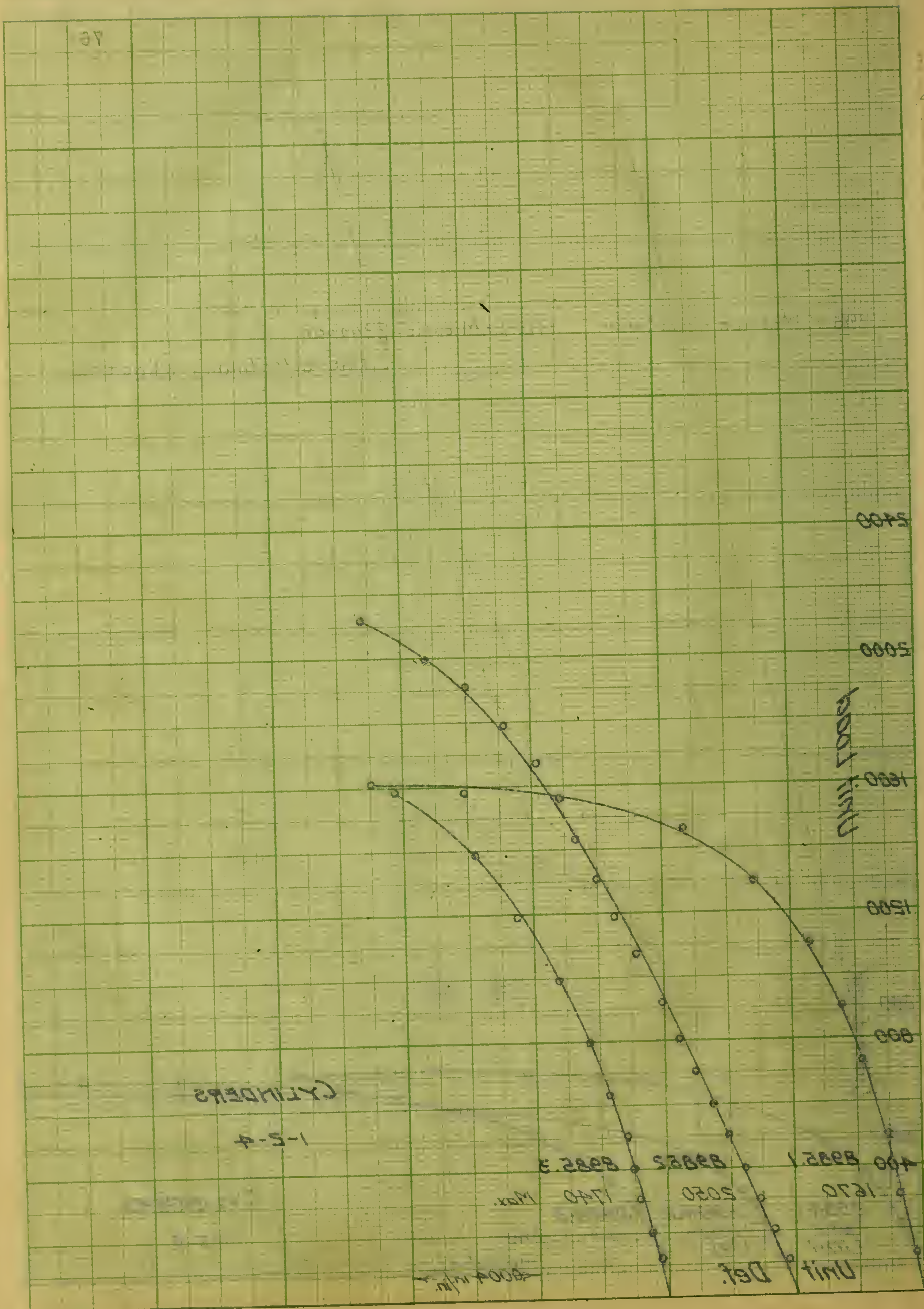
1670
8985.2
2050
8985.3
1740
Max.
Unit Def.
.0004 in/in.
CYLINDERS
1-2-4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8985.3
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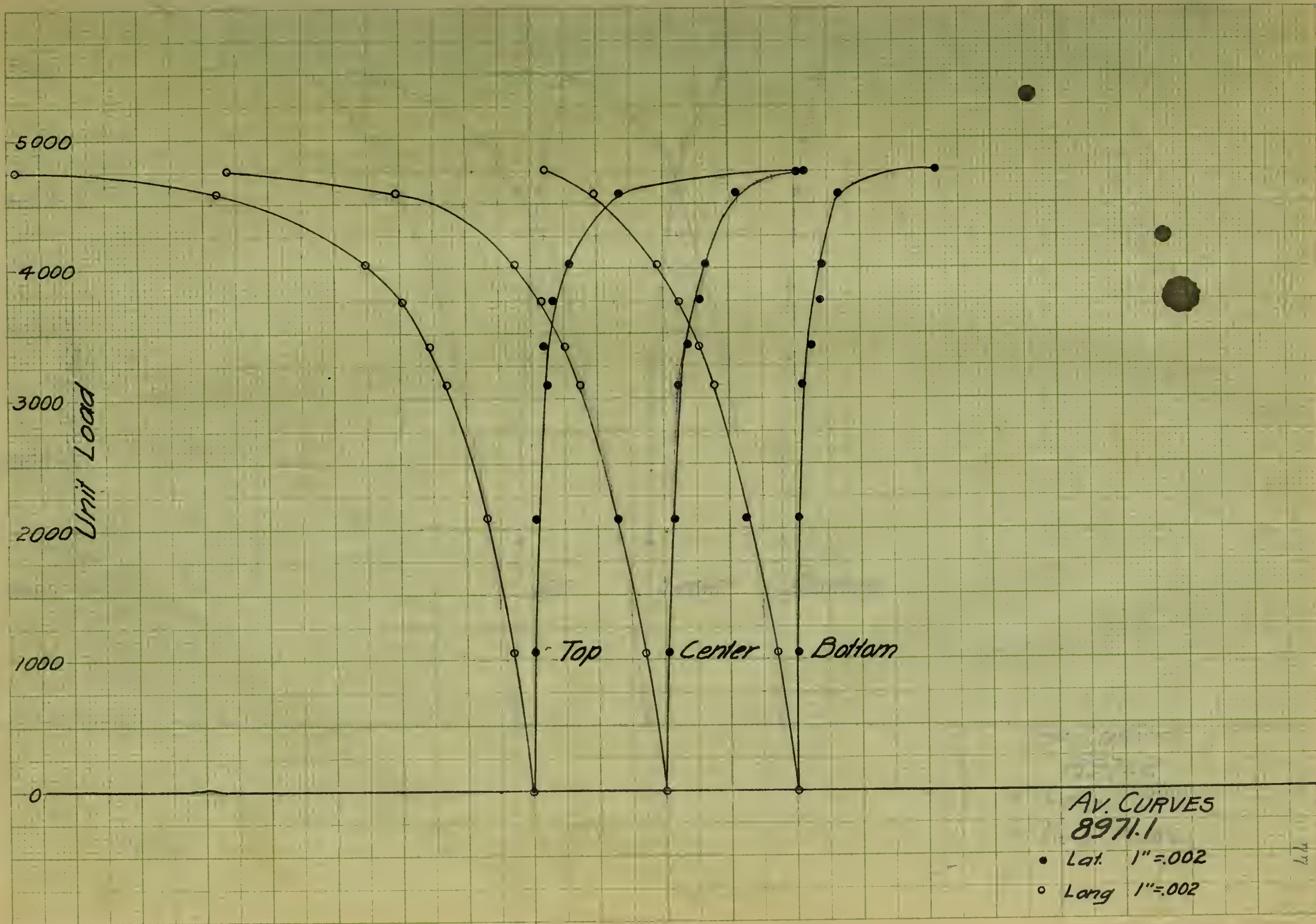
2050
1740 Max.
CYLINDERS
1-2-4
Unit Def.
.0004 in/in.



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Center
Bottom
Av. CURVES
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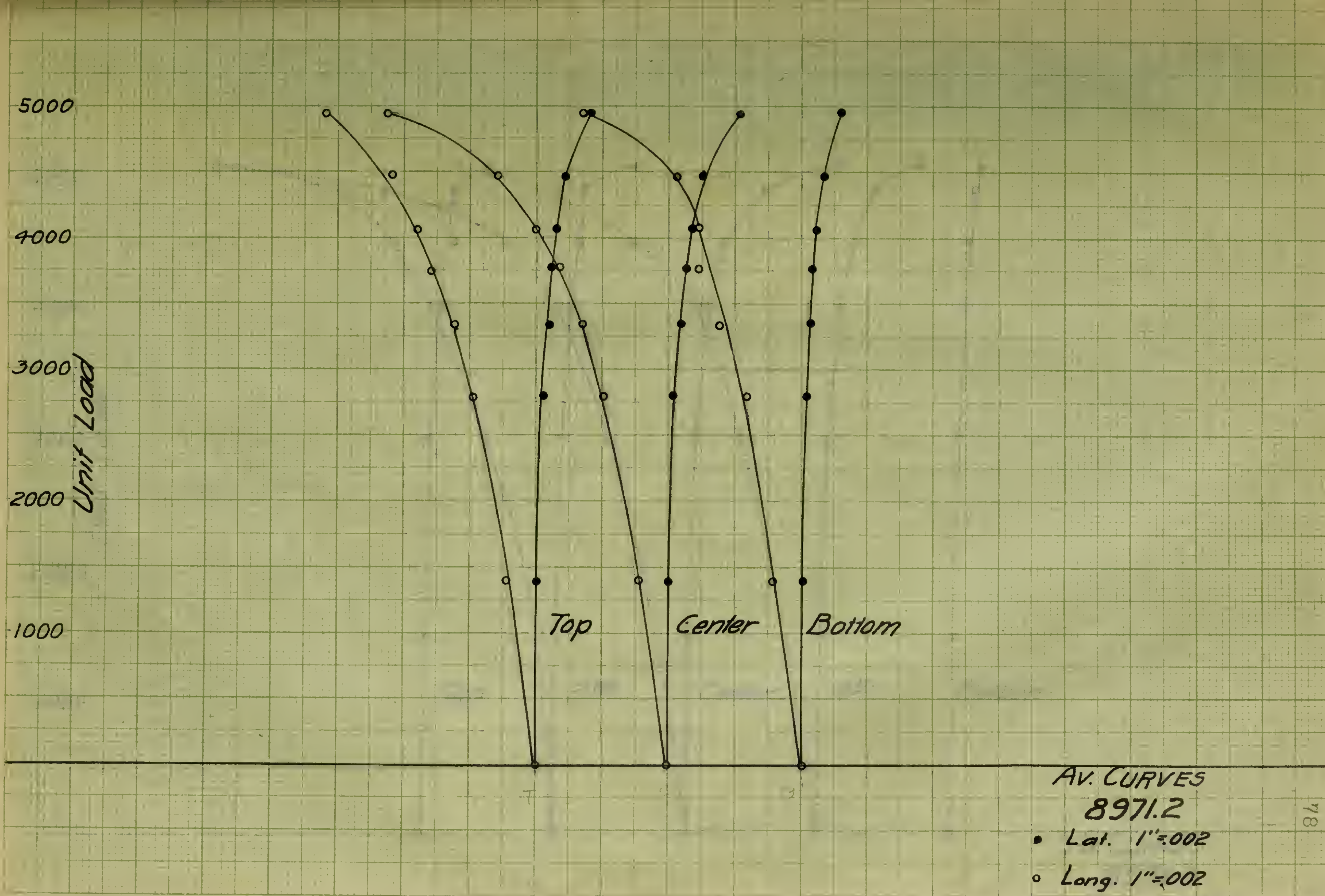
Long 1"=.002



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Bottom
Av. CURVES
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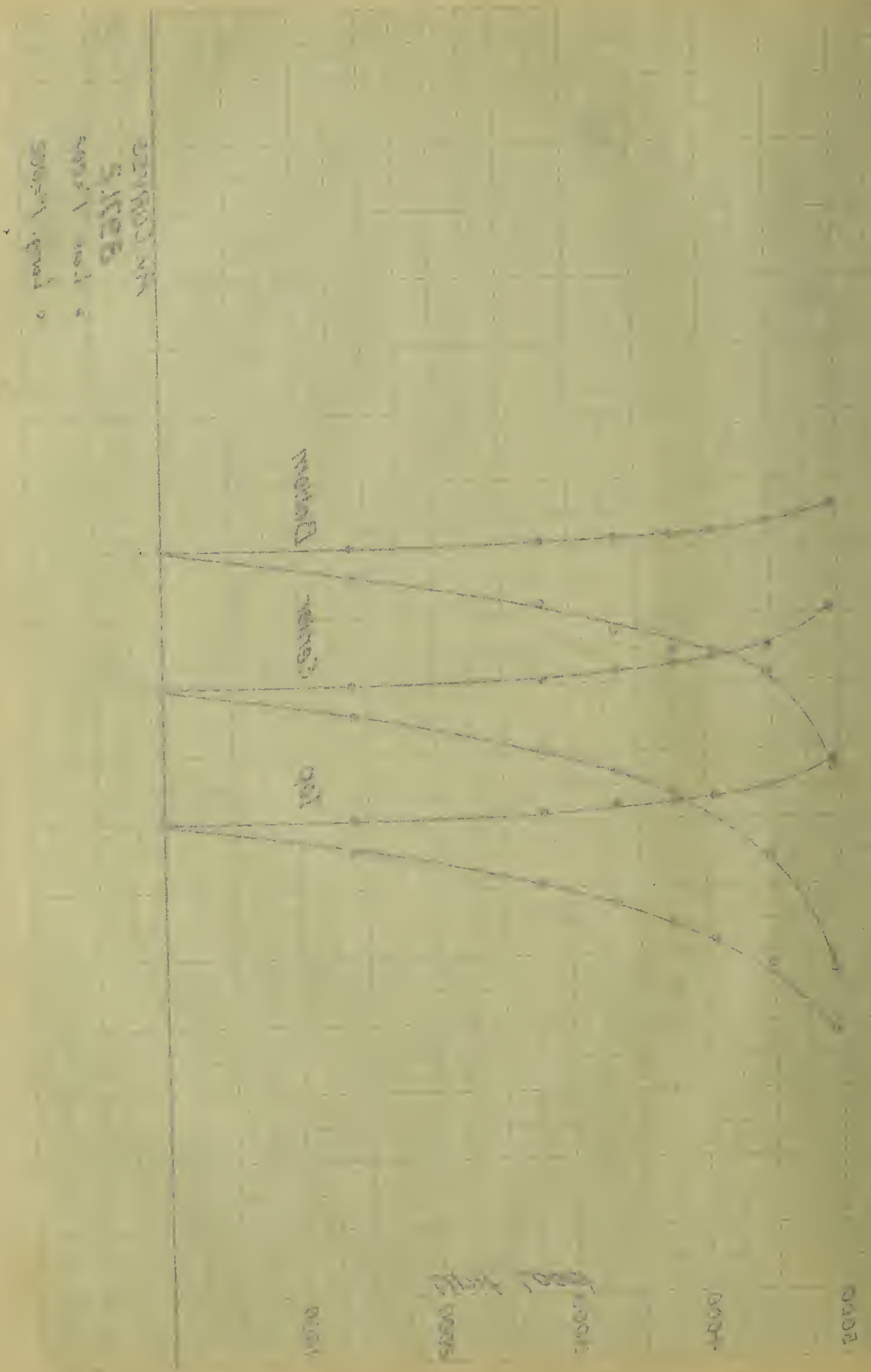
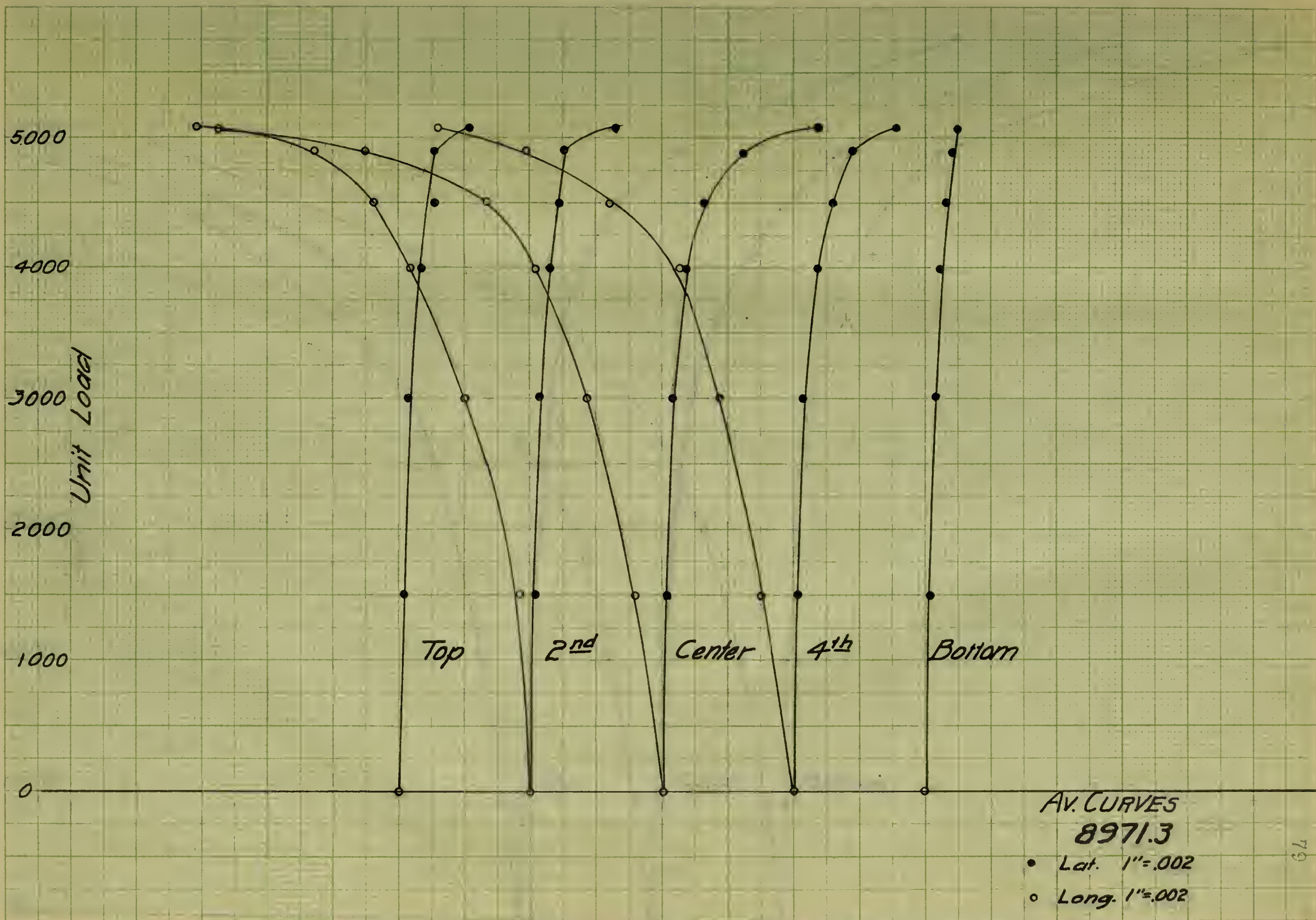
o Long. 1"=.002





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Center
4th
Bottom
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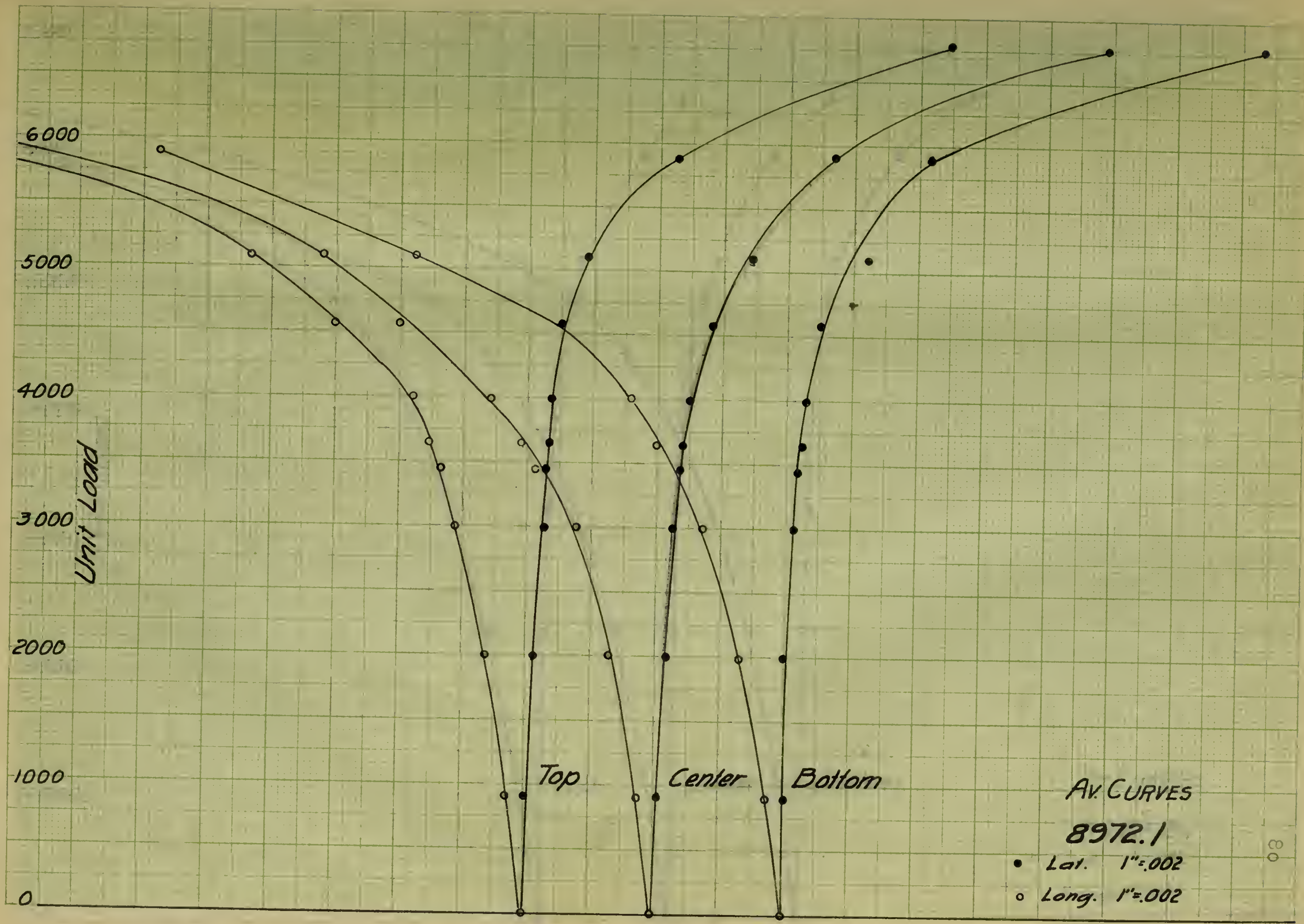
Long. 1"=.002

79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Center
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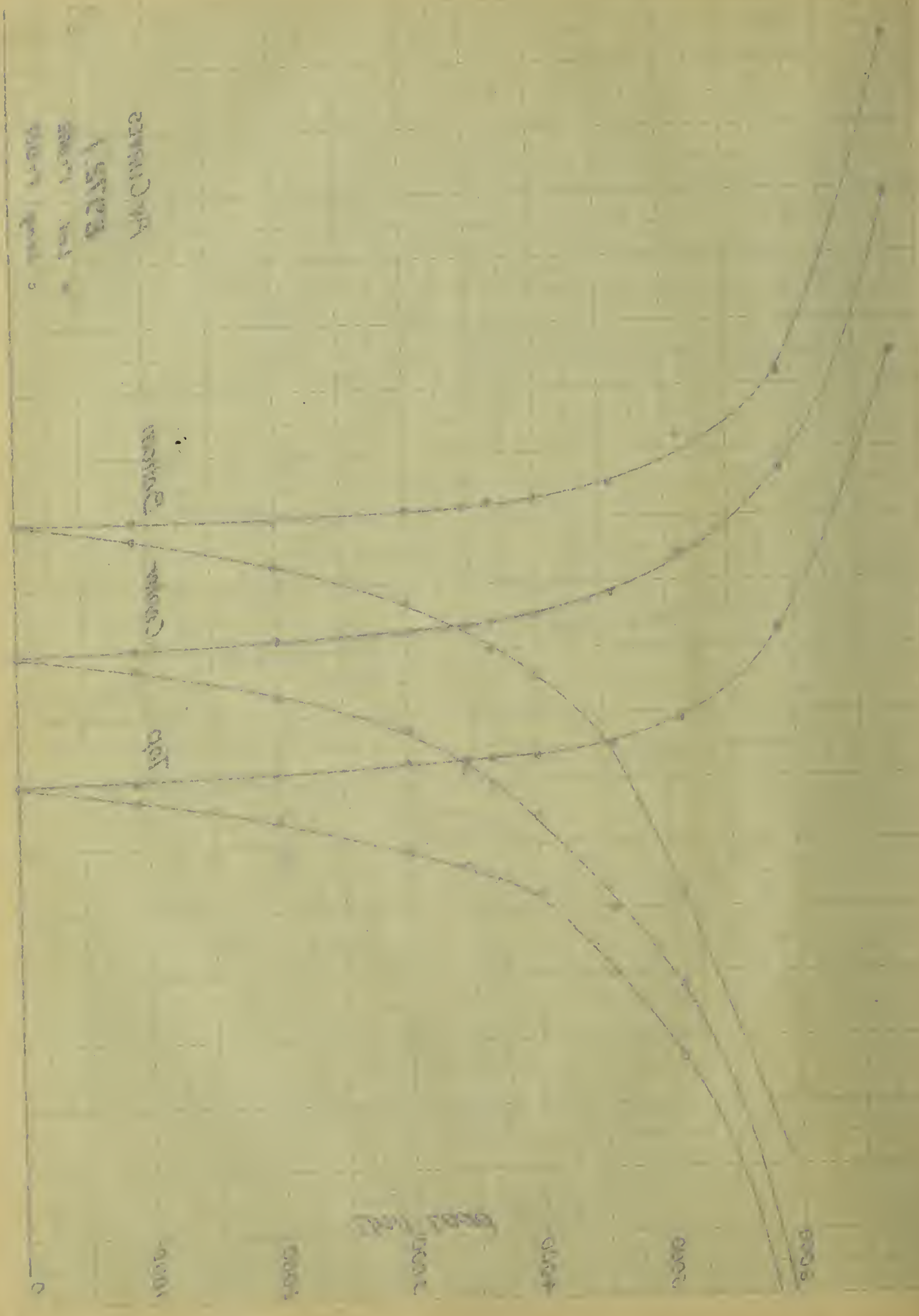

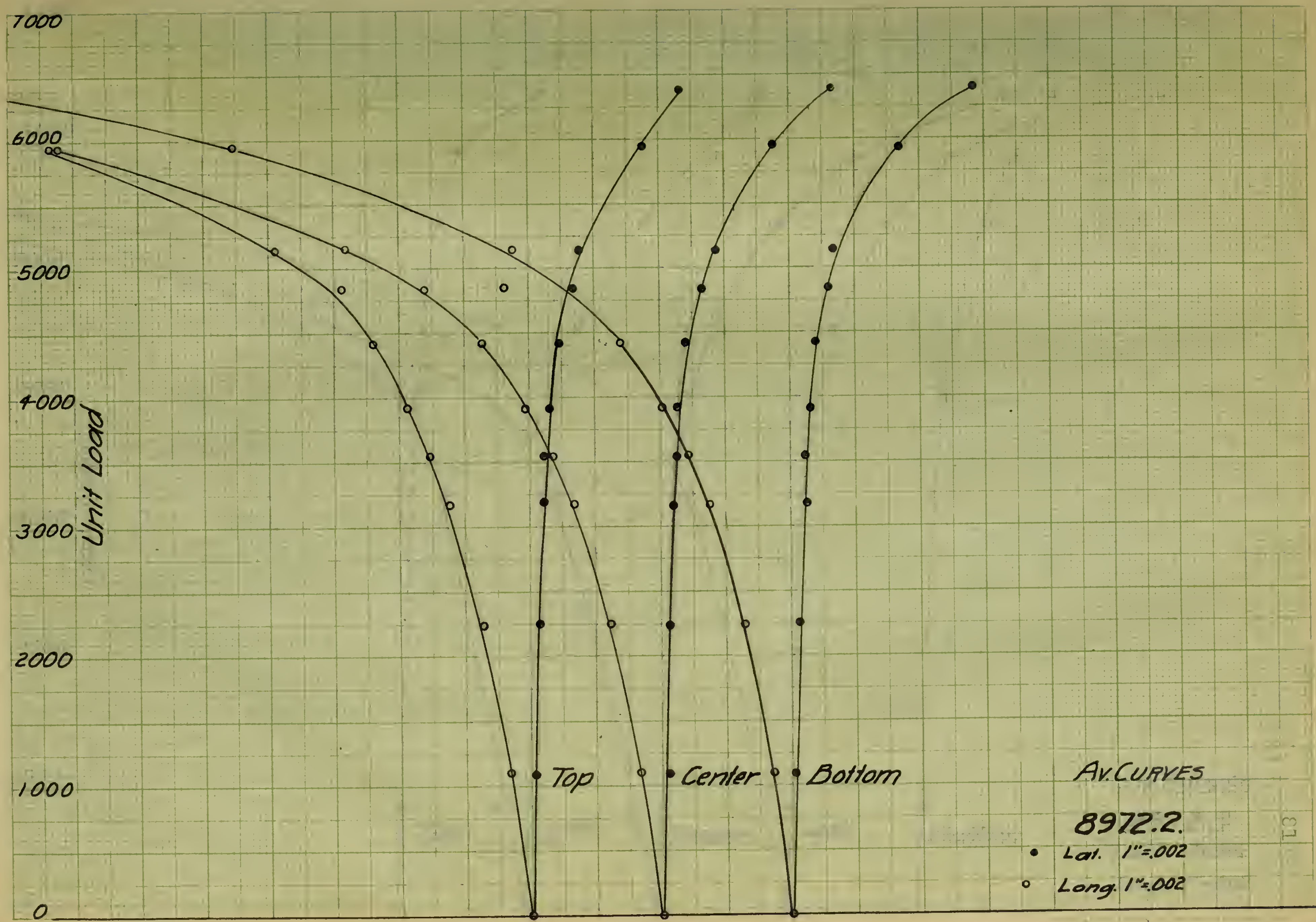
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Center
Bottom
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Lat. 1"=.002
Long. 1"=.002

7000
6000
5000
4000
3000
2000
1000
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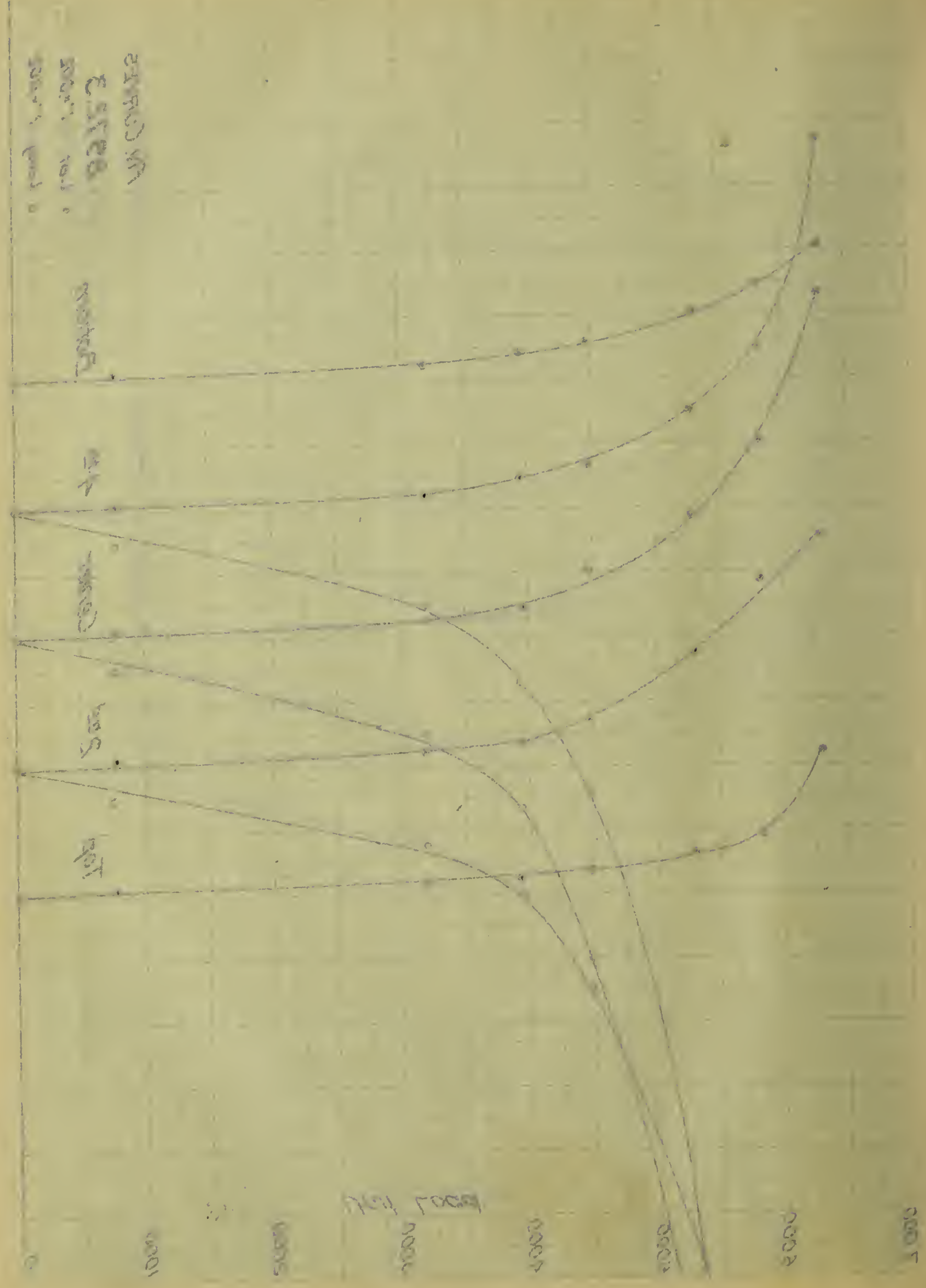
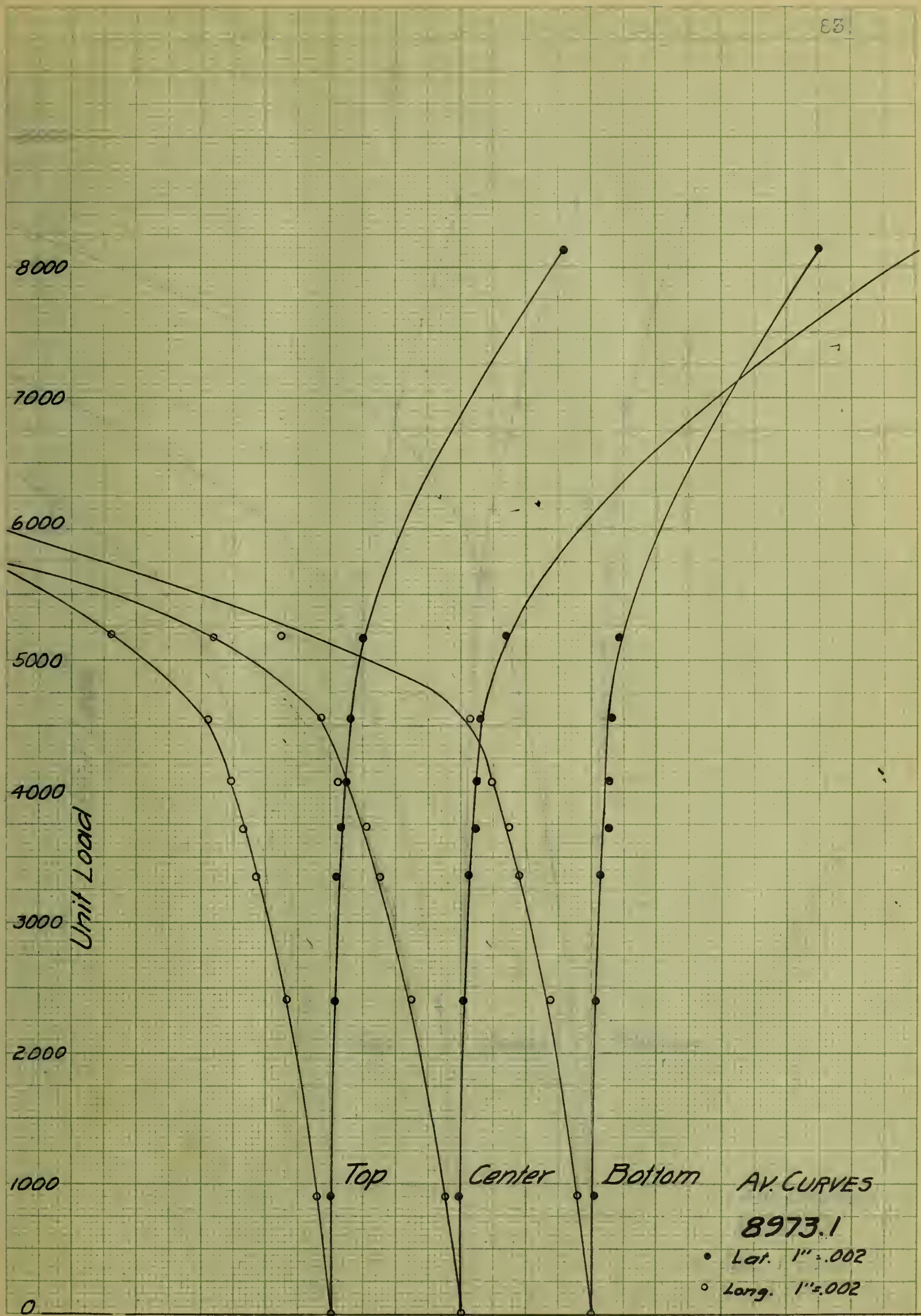
Top
2nd
Center
4th
Bottom
Av. CURVES
8972.3
• Lat. 1"=.002
o Long. 1"=.002

82





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5000
4000
3000
2000
1000
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Center
Bottom
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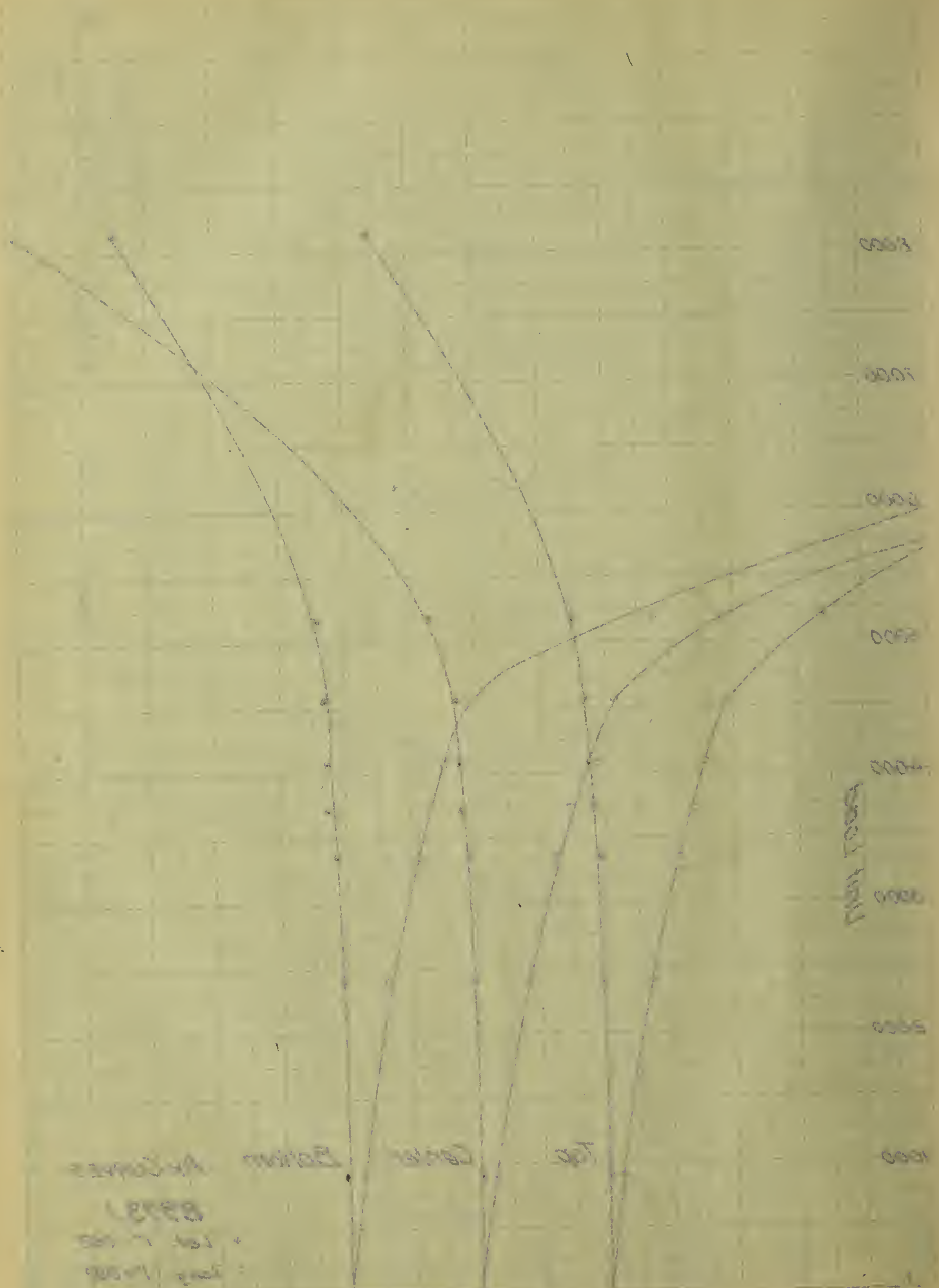
○ Long. 1" = .002



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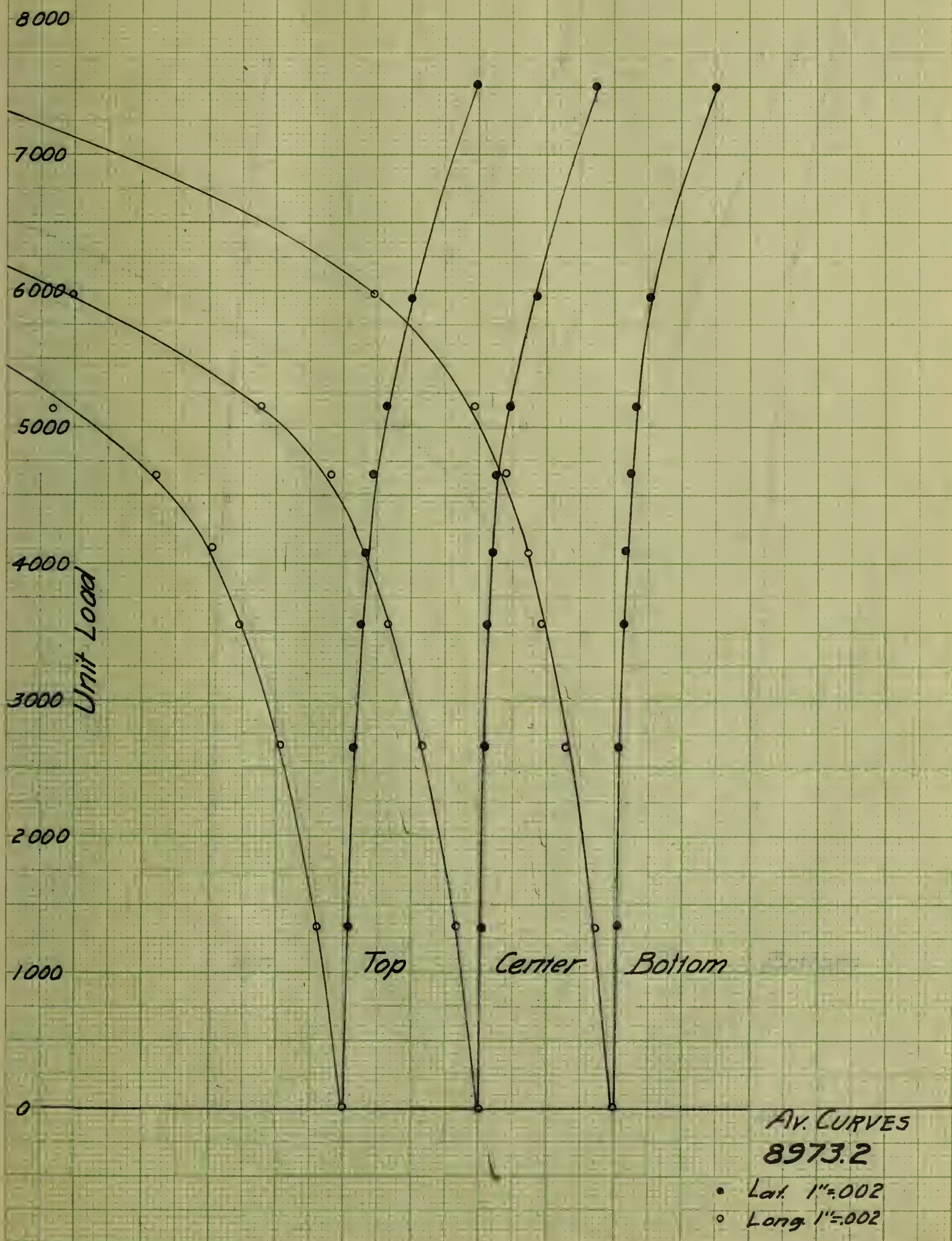
4000
3000
2000
1000
Top
Center
Bottom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4000
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2000
1000
0
Unit Load
Top
Center
Bottom
Av. Curves
8973.2
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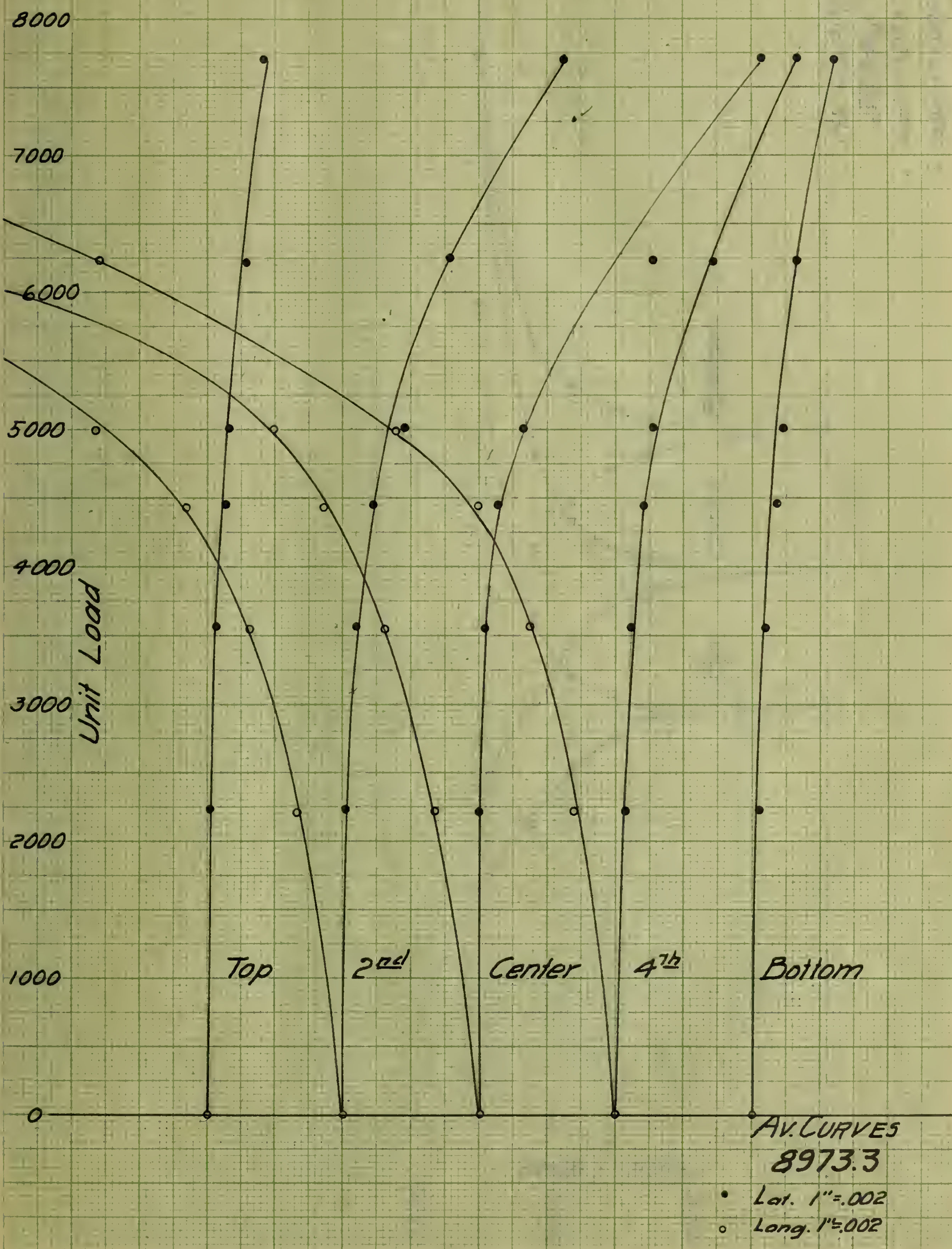
Long. 1"=.002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2000
1000
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Unit Load
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2nd
Center
4th
Bottom
Av. Curves
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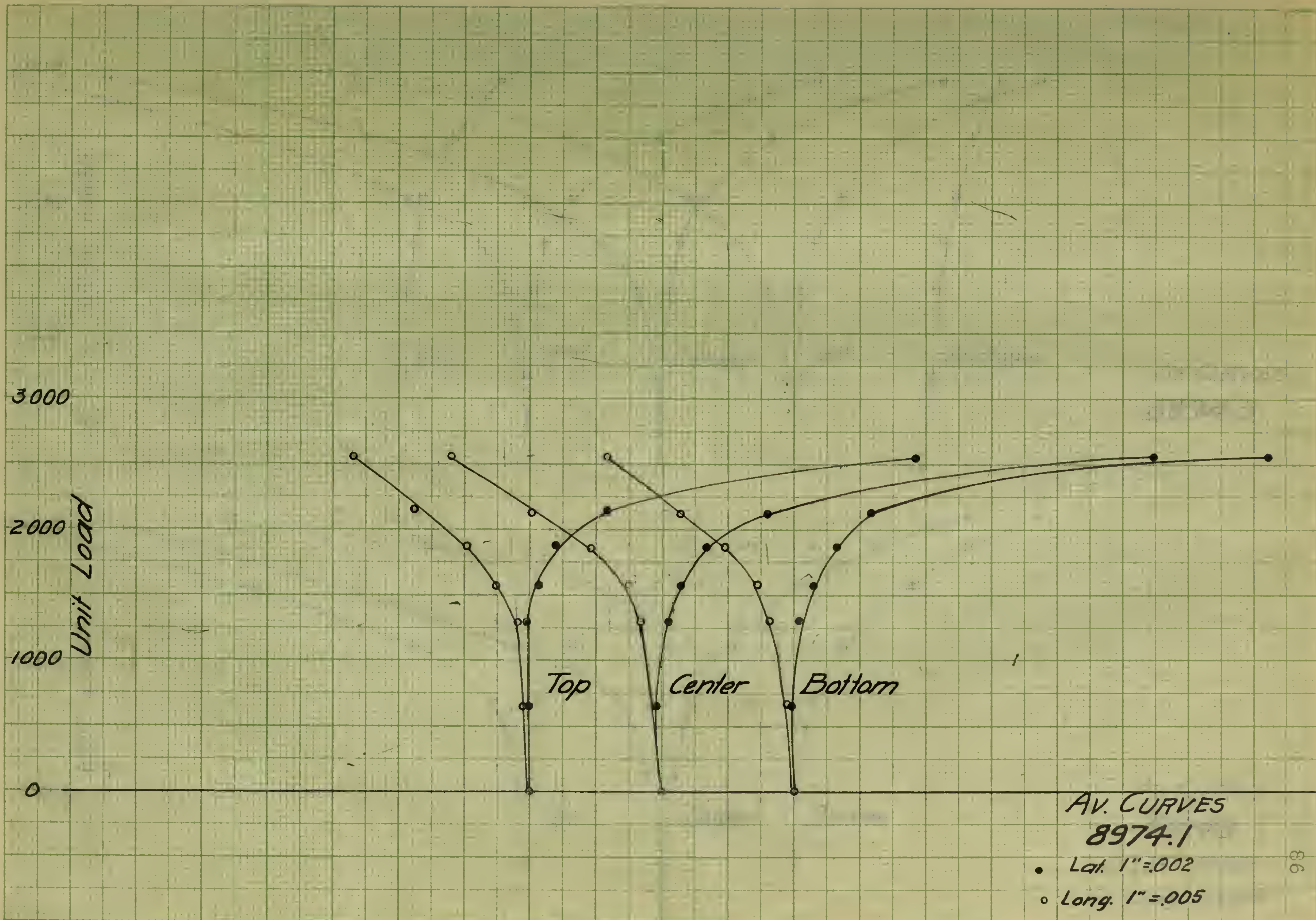
Long. 1" = .002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Unit Load
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Center
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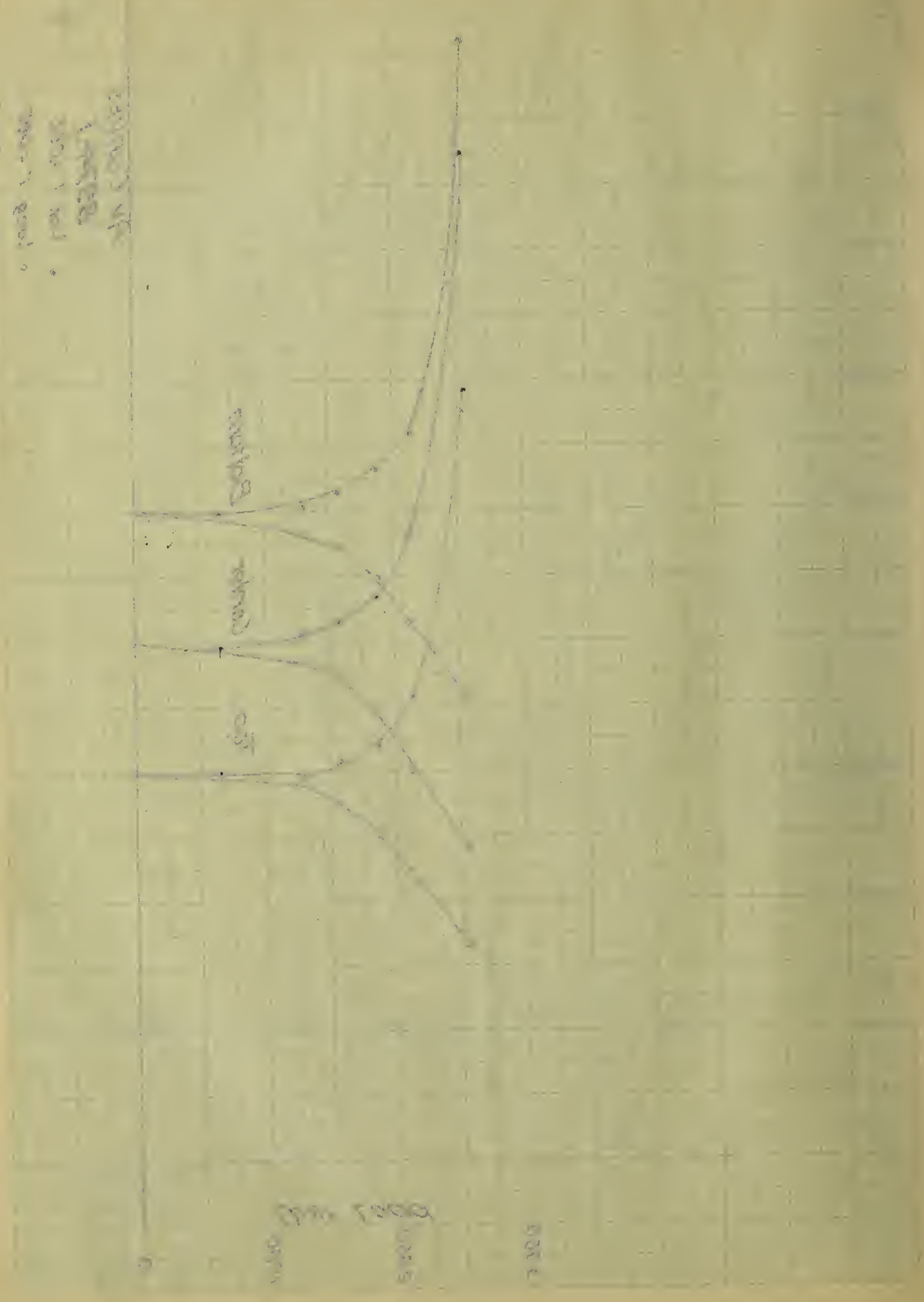

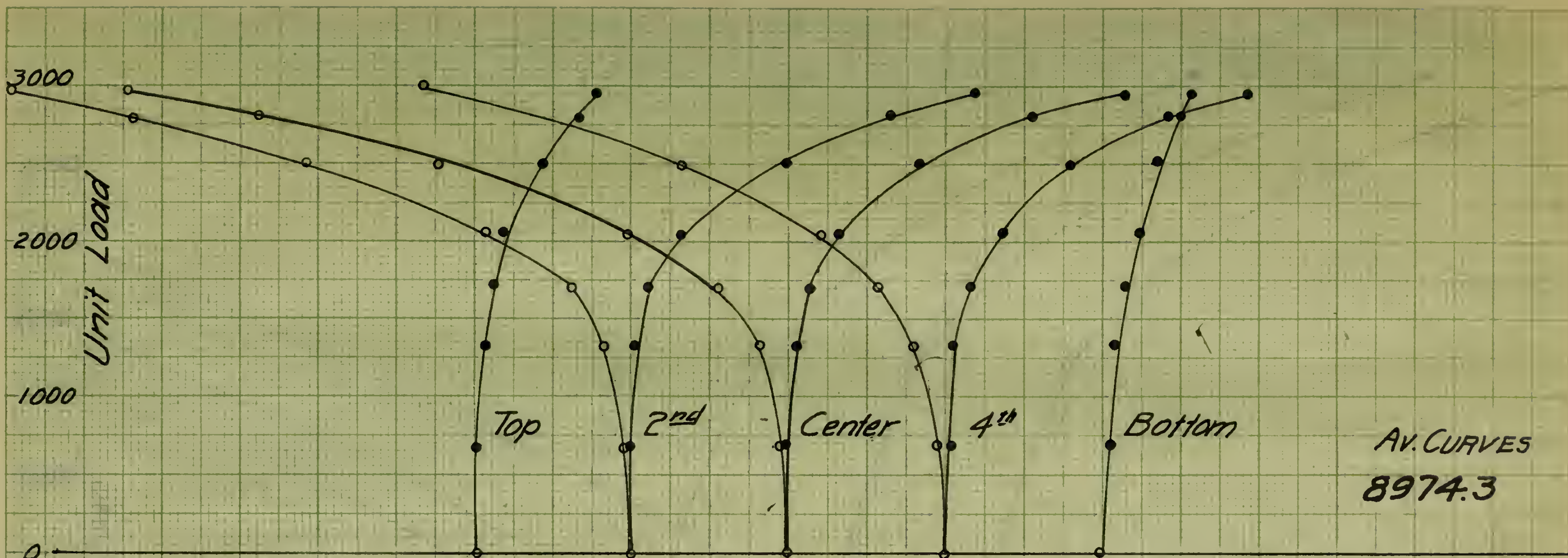
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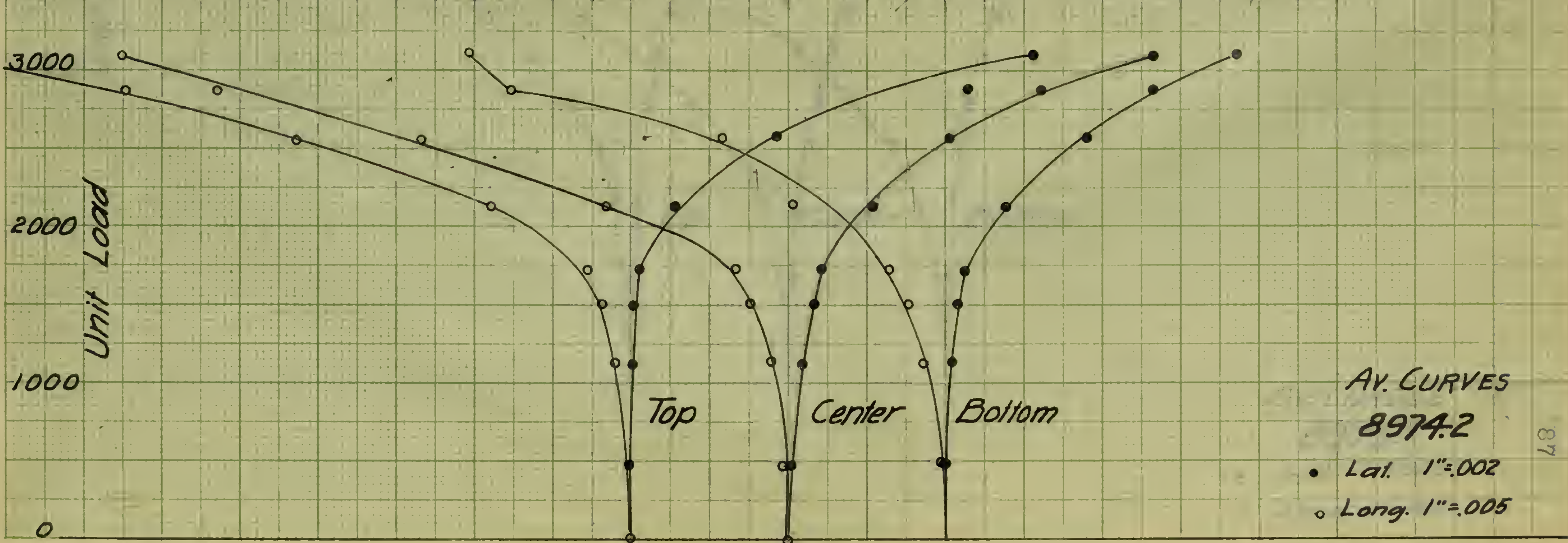
Center
4th
Bottom
Av. CURVES
8974.3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1000
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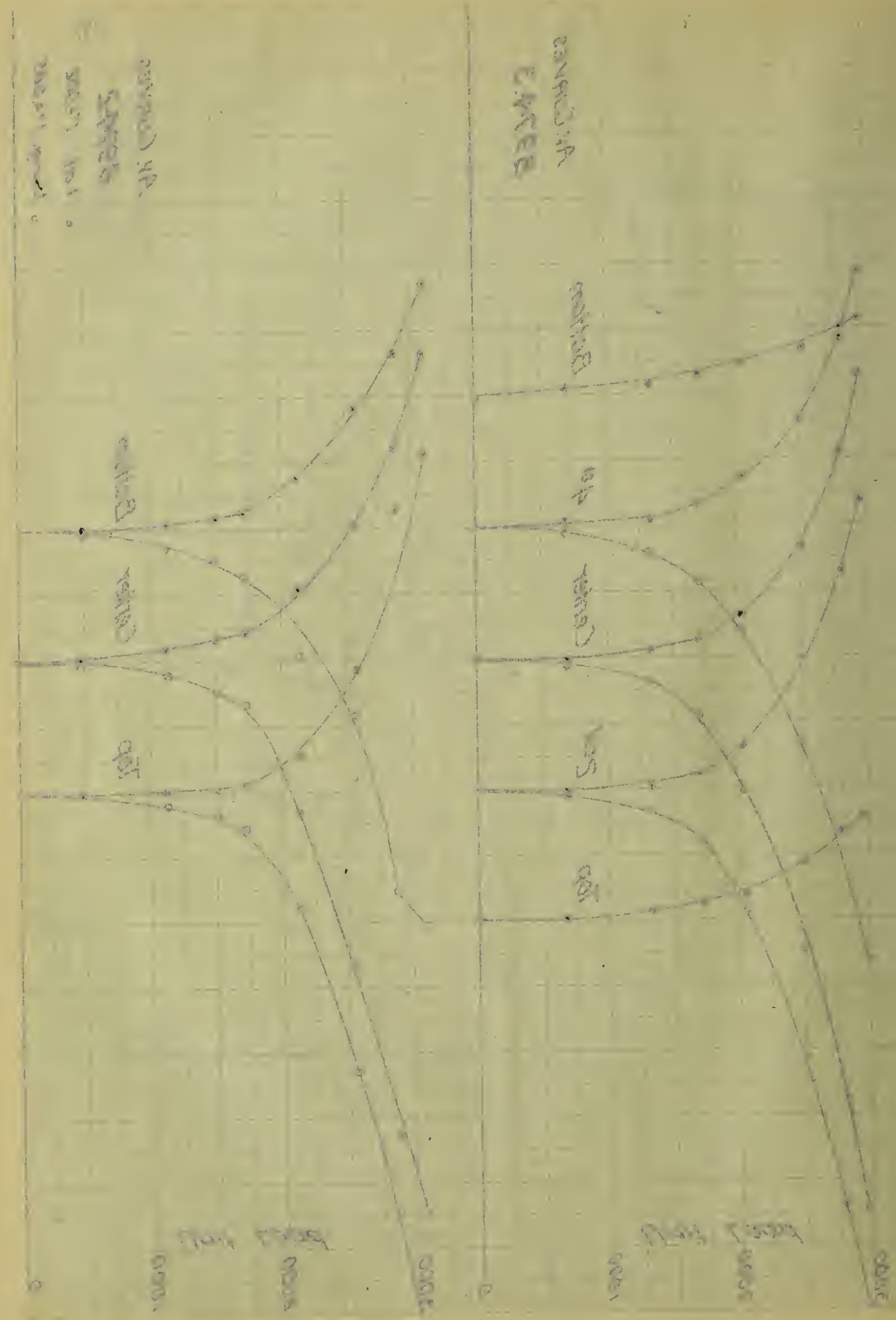
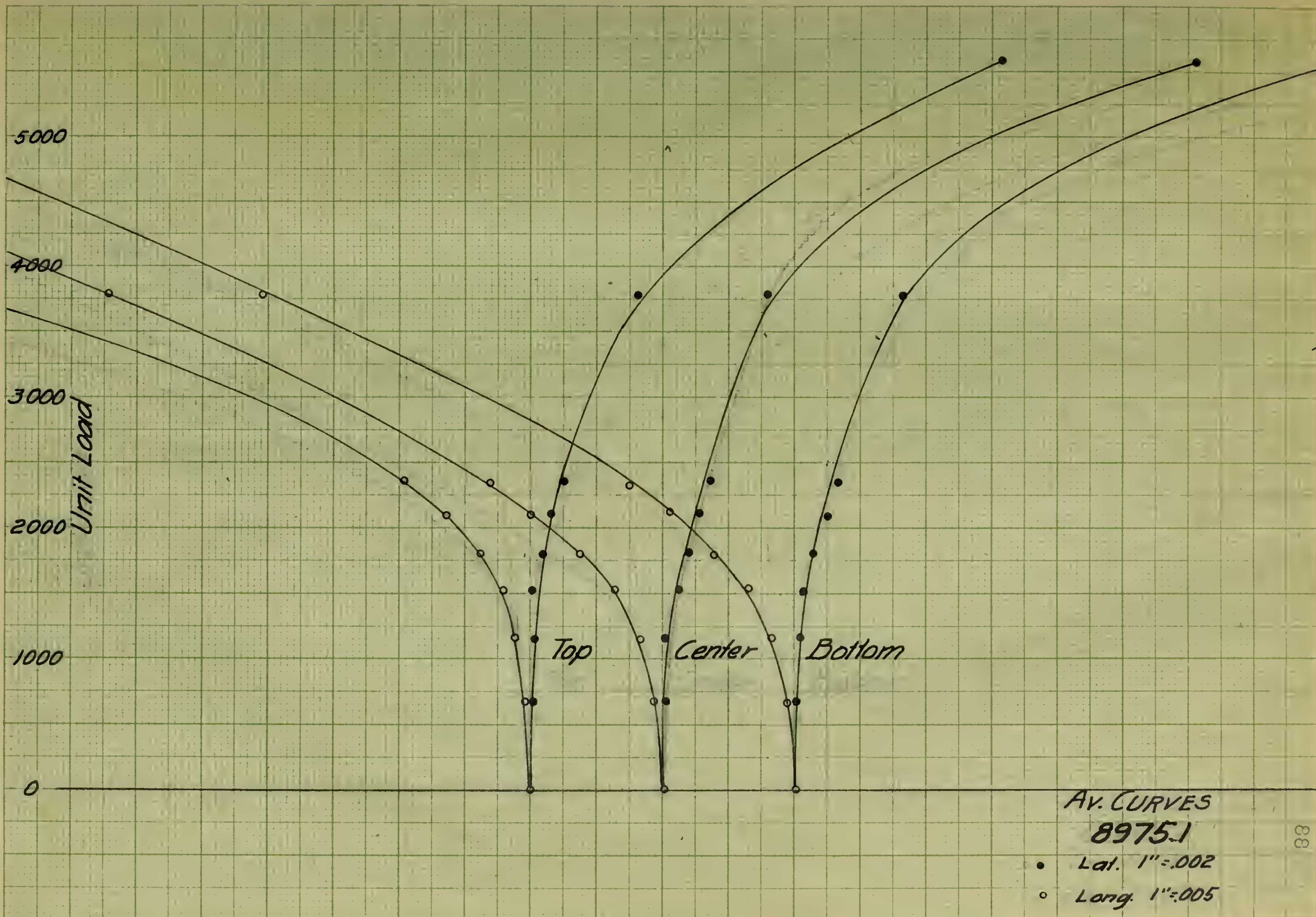
Unit Load
Top
Center
Bottom
Av. CURVES
8974.2
• Lat. 1" = .002
∘ Long. 1" = .005

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2000
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Unit Load
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Center
Bottom
Av. CURVES
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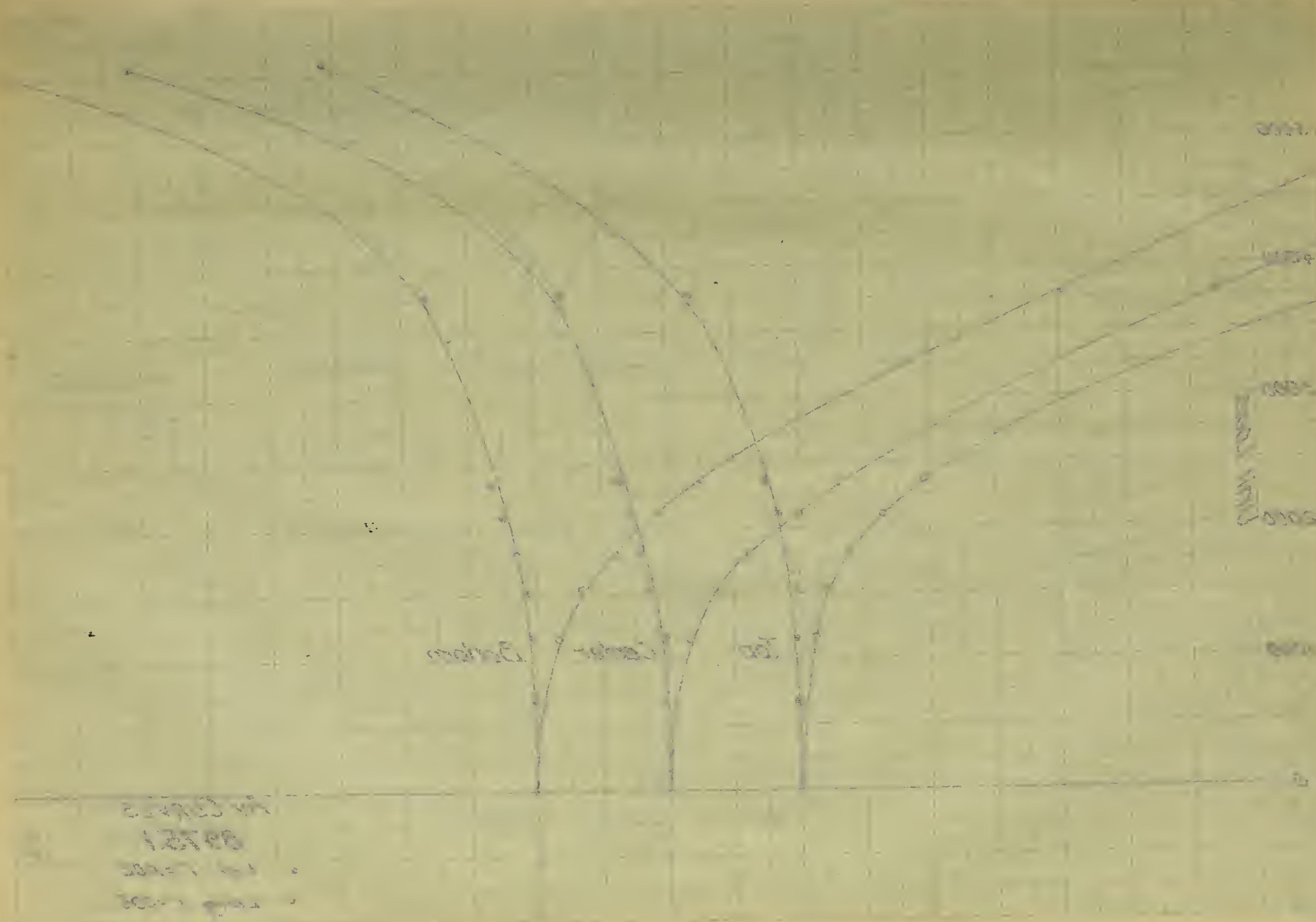
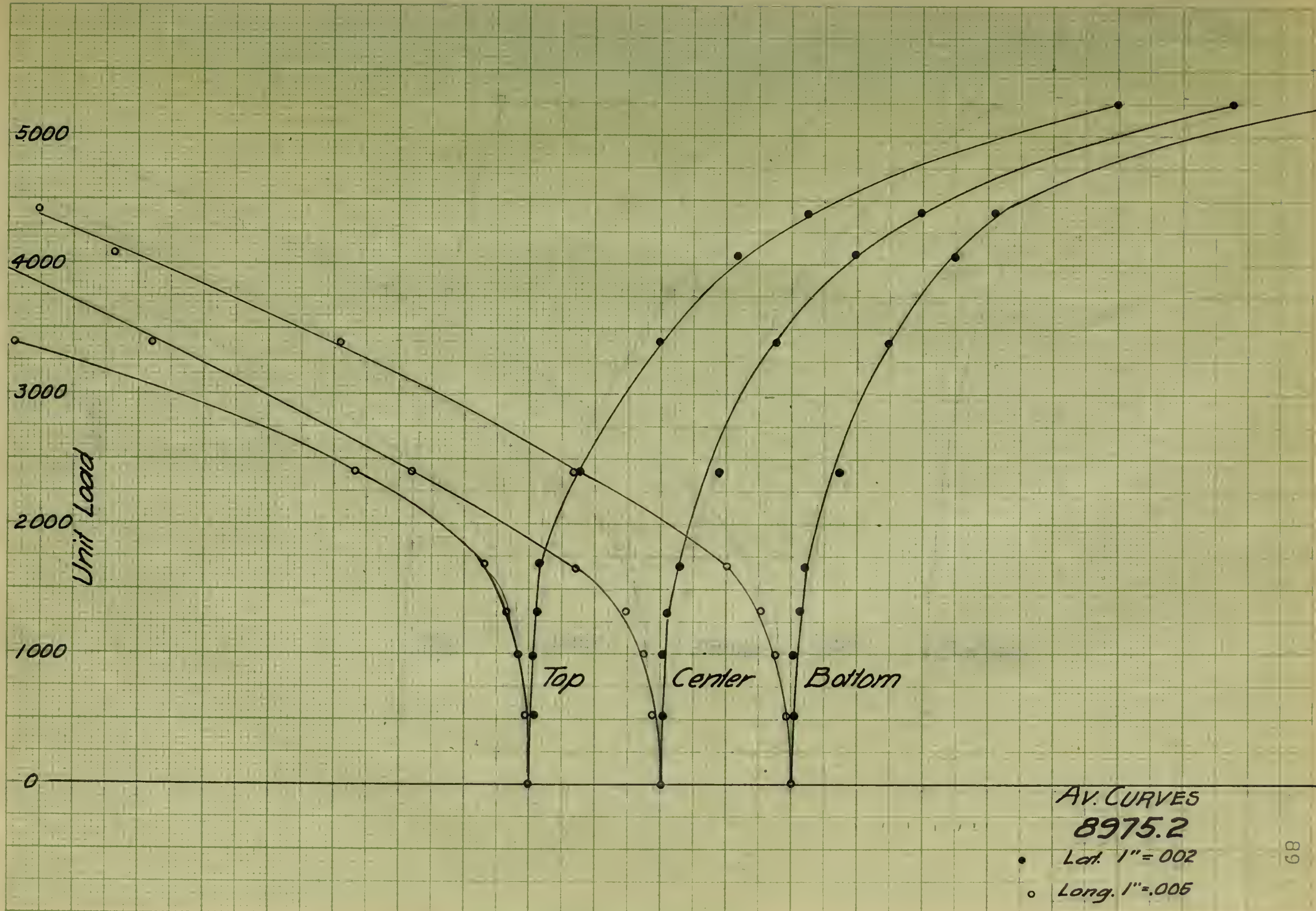
● Lat. 1" = .002
○ Long. 1" = .005

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Unit Load
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Center
Bottom
Av. CURVES
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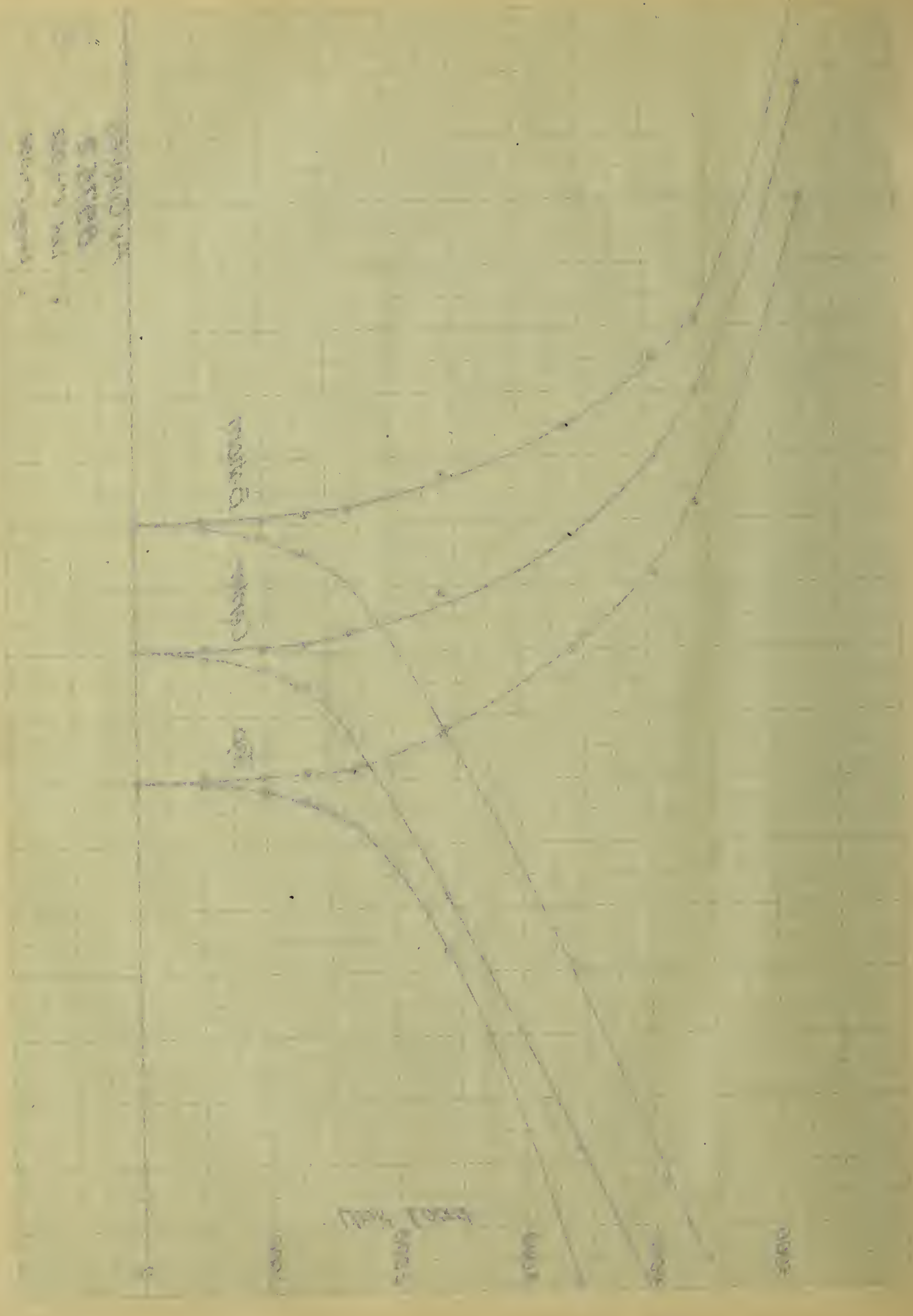
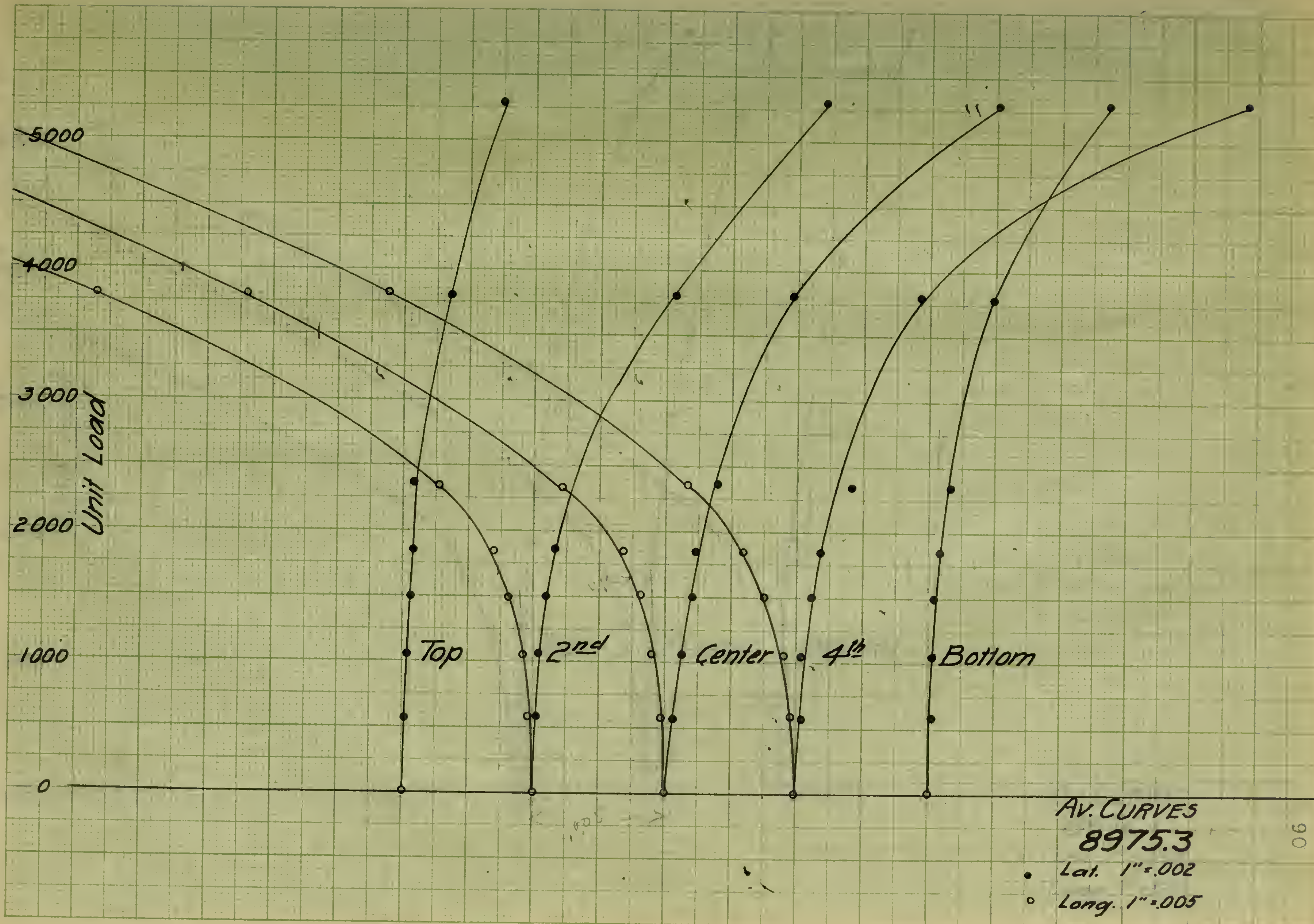
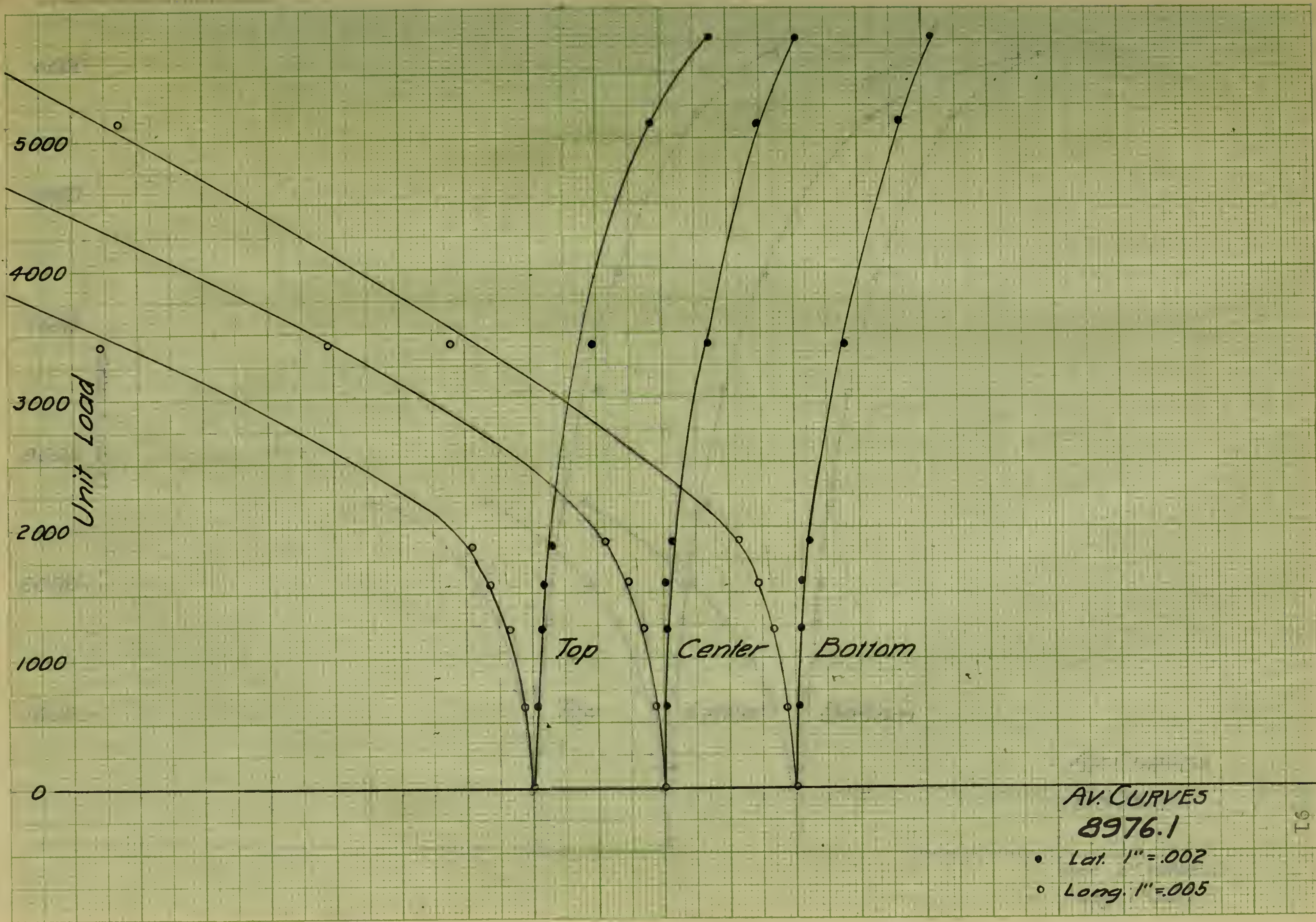




5000
4000
3000
2000
1000
0
Unit Load
Top
2nd
Center
4th
Bottom
Av. CURVES
8975.3
Lat. 1" = .002
Long. 1" = .005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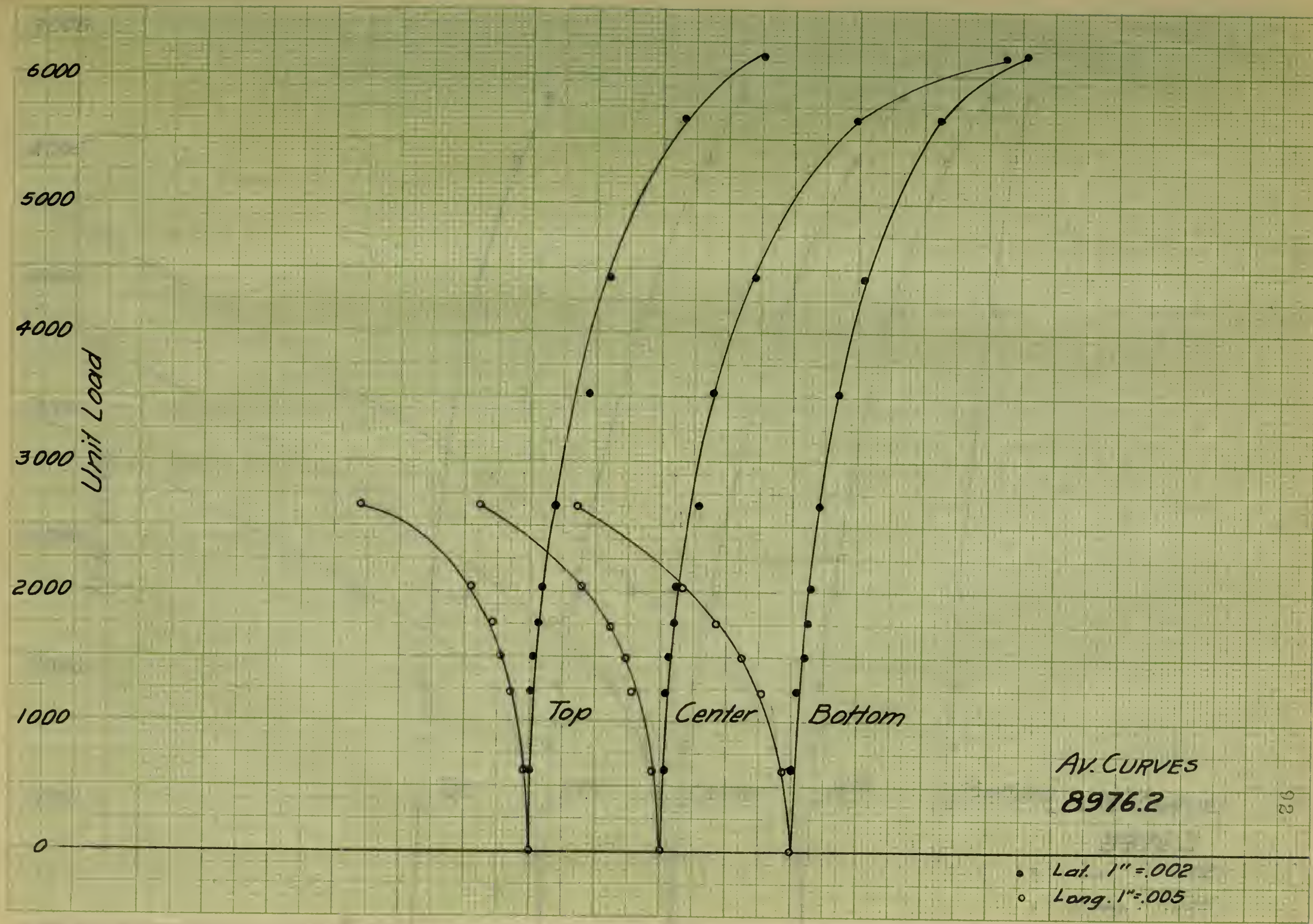
2000
1000
0
Top
Center
Bottom
Av. CURVES
8976.1
Lat. 1" = .002
Long. 1" = .005
91



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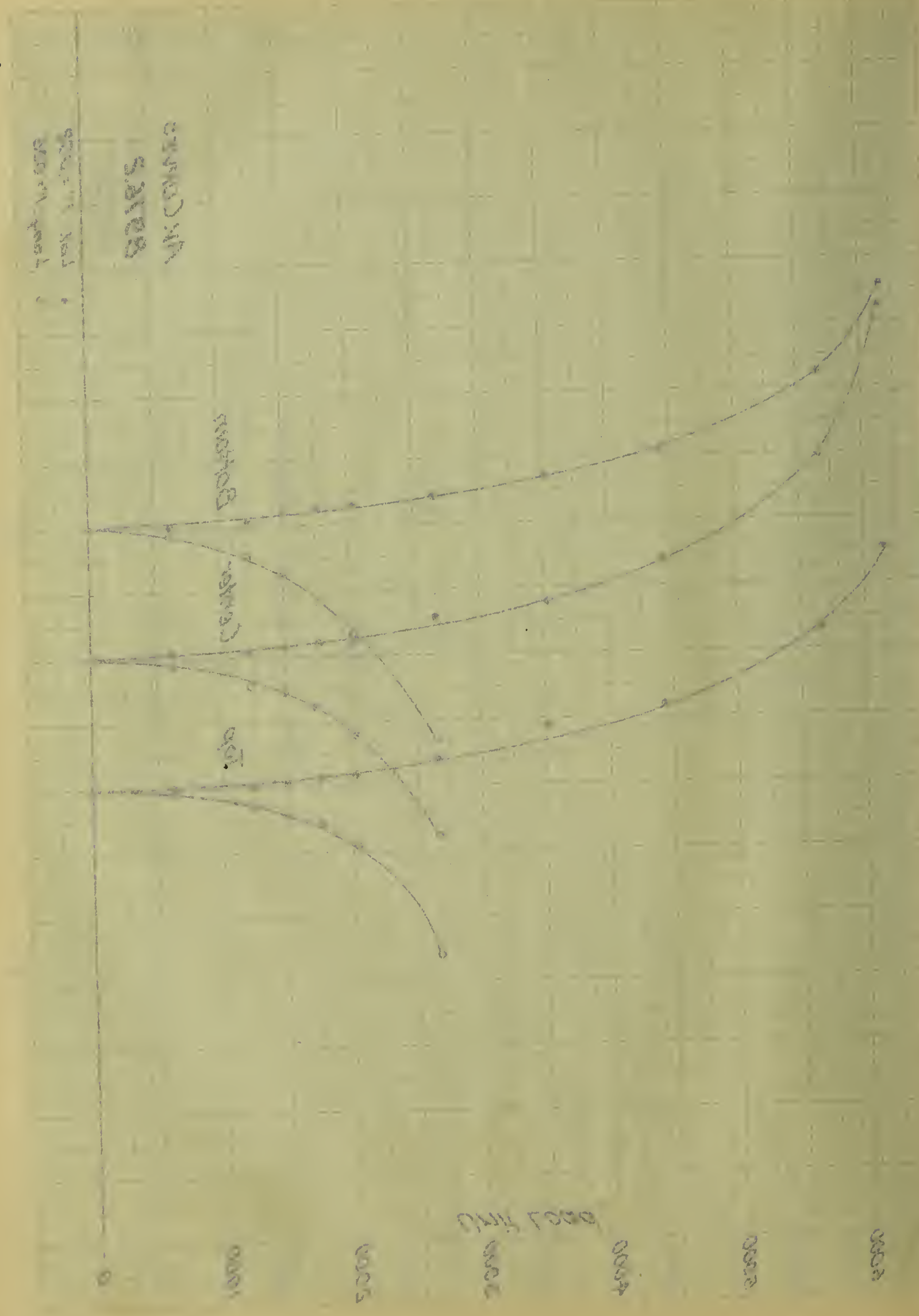
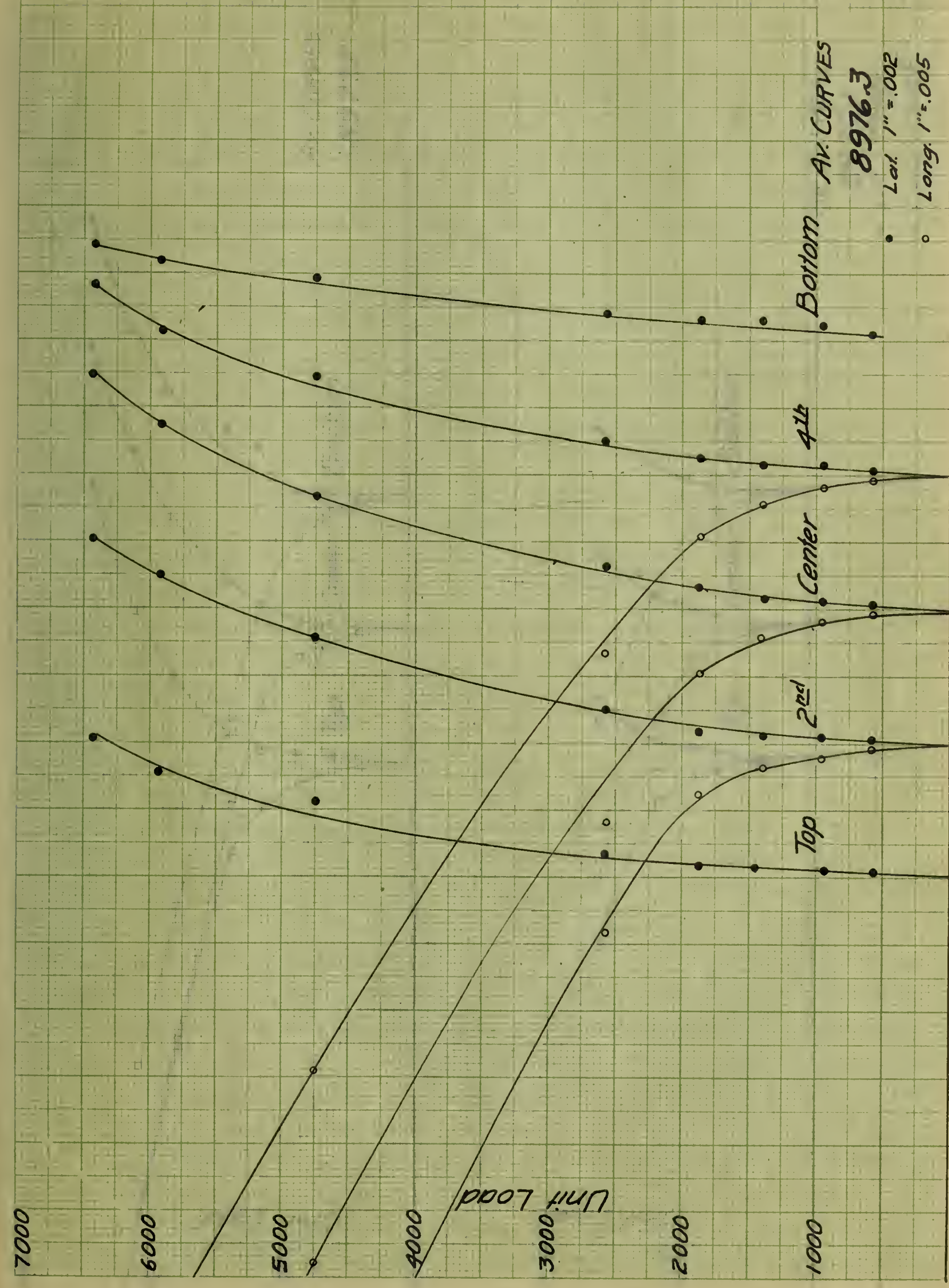
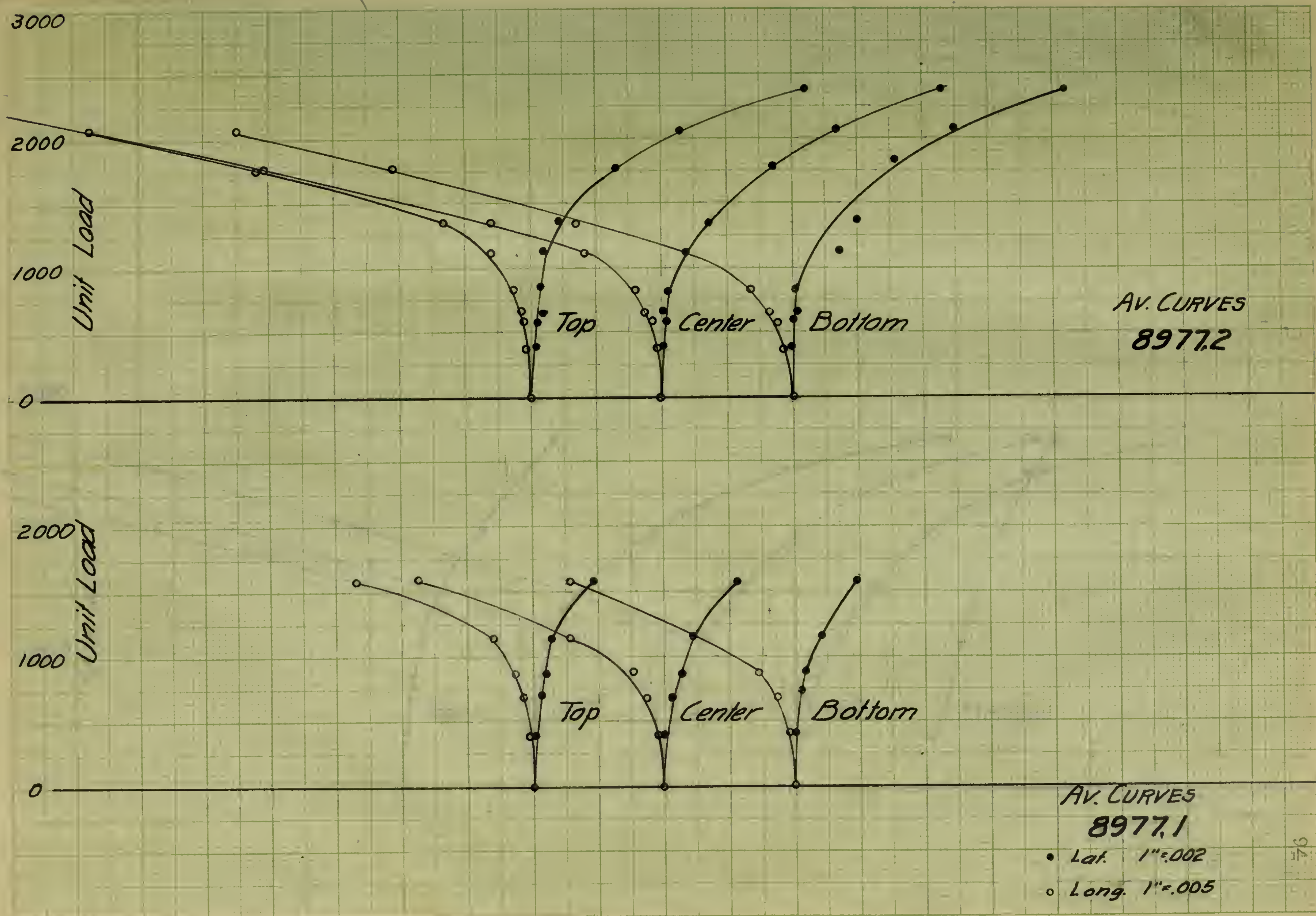
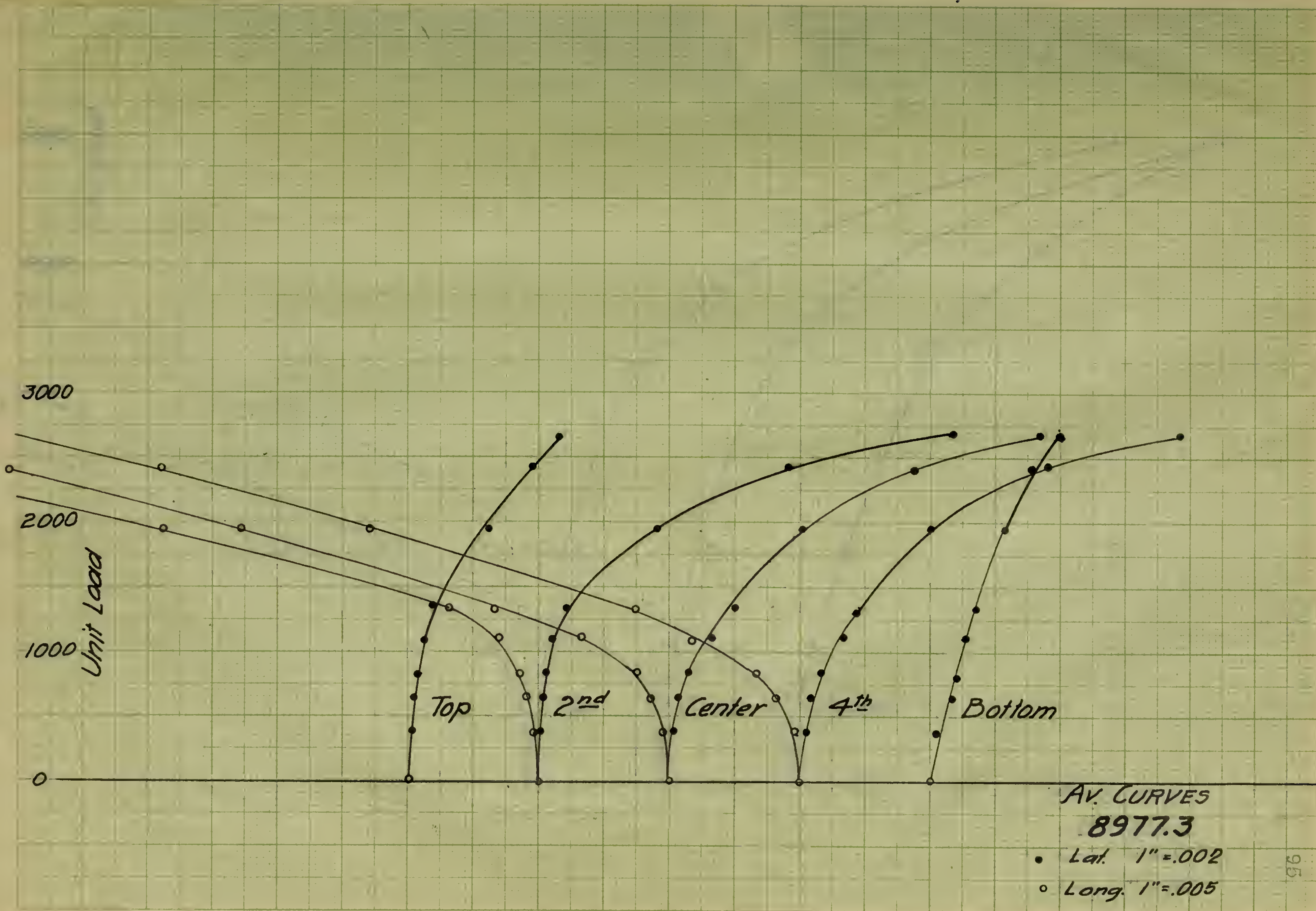
4000
3000
2000
1000
0
Unit Load
Top
Center
Bottom
AV. CURVES
8976.2
Lat. 1" = .002
Long. 1" = .005
92

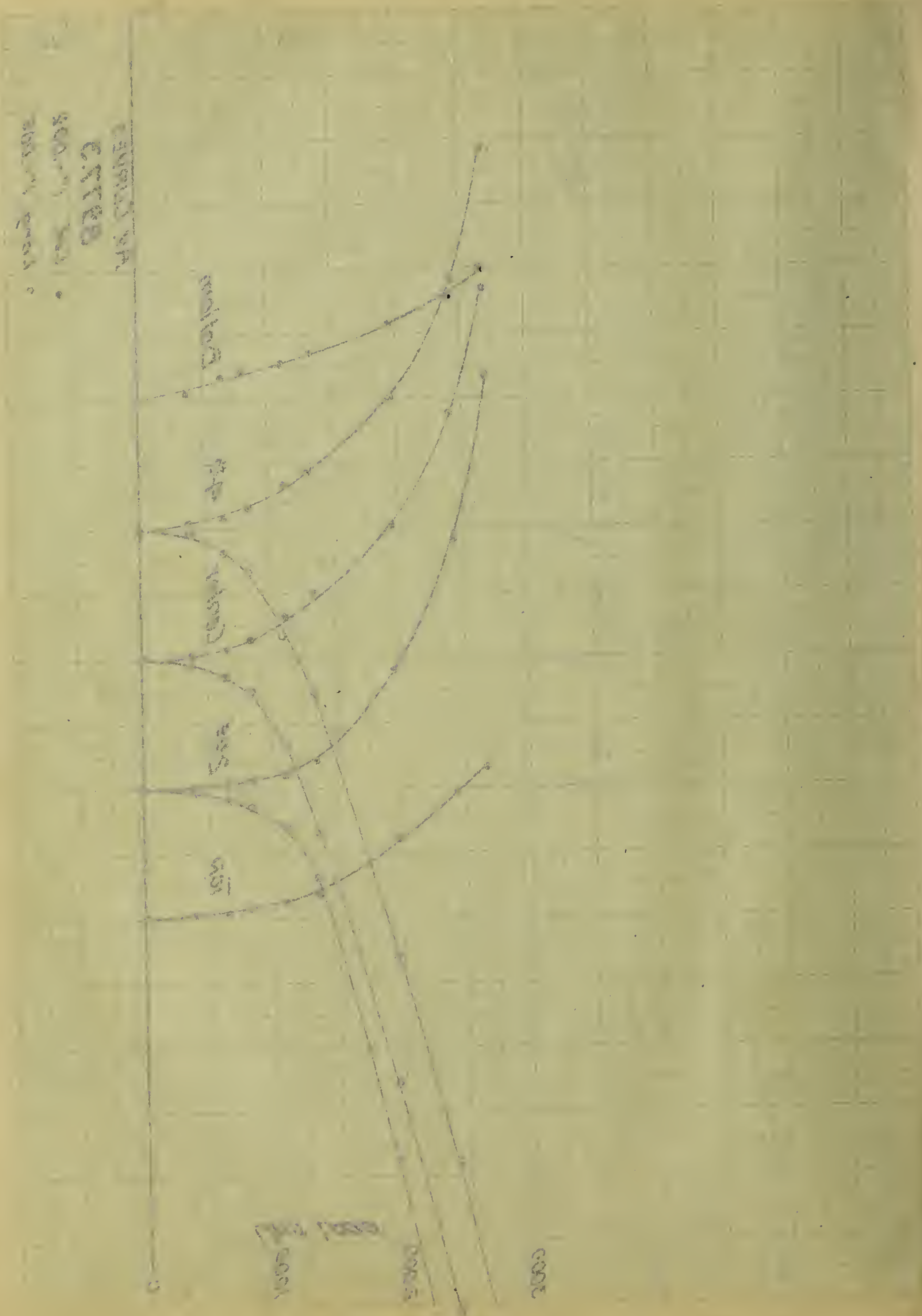


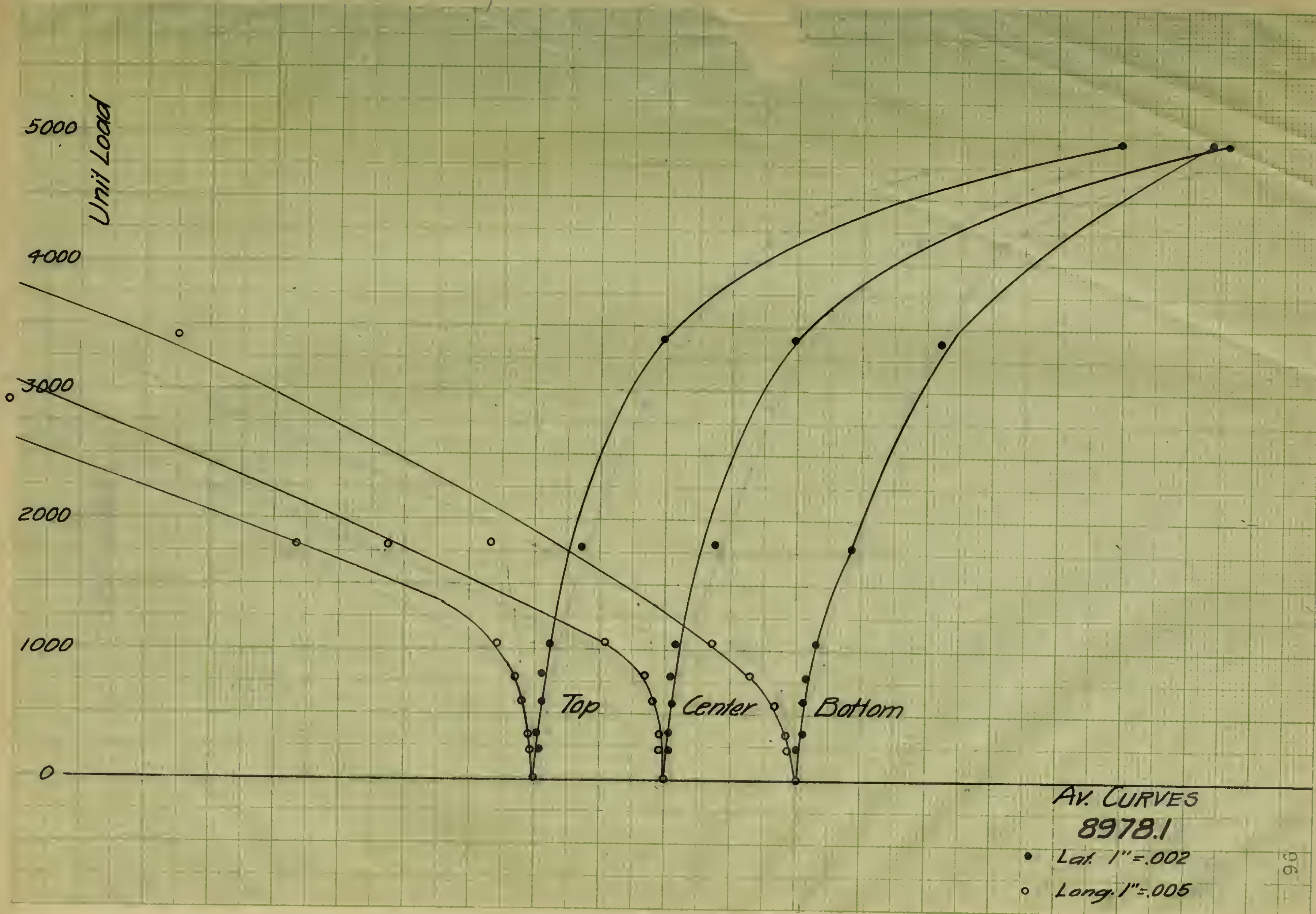
Unit Load
Top
Center
Bottom

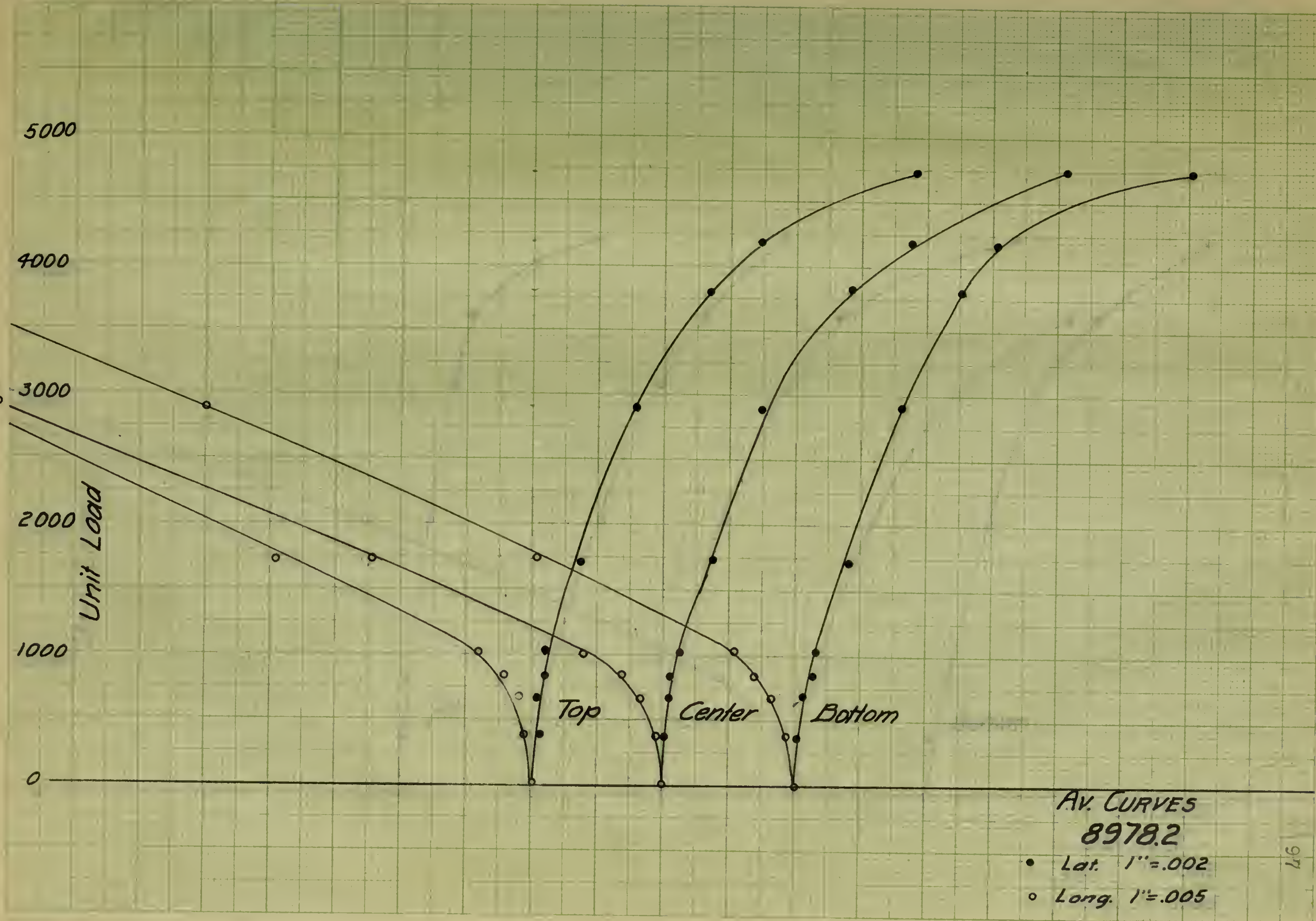

Av. CURVES
8976.3
Lat. 1" = .002
Long. 1" = .005
Bottom
4th
Center
2nd
Top
Unit Load
7000
6000
5000
4000
3000
2000
1000

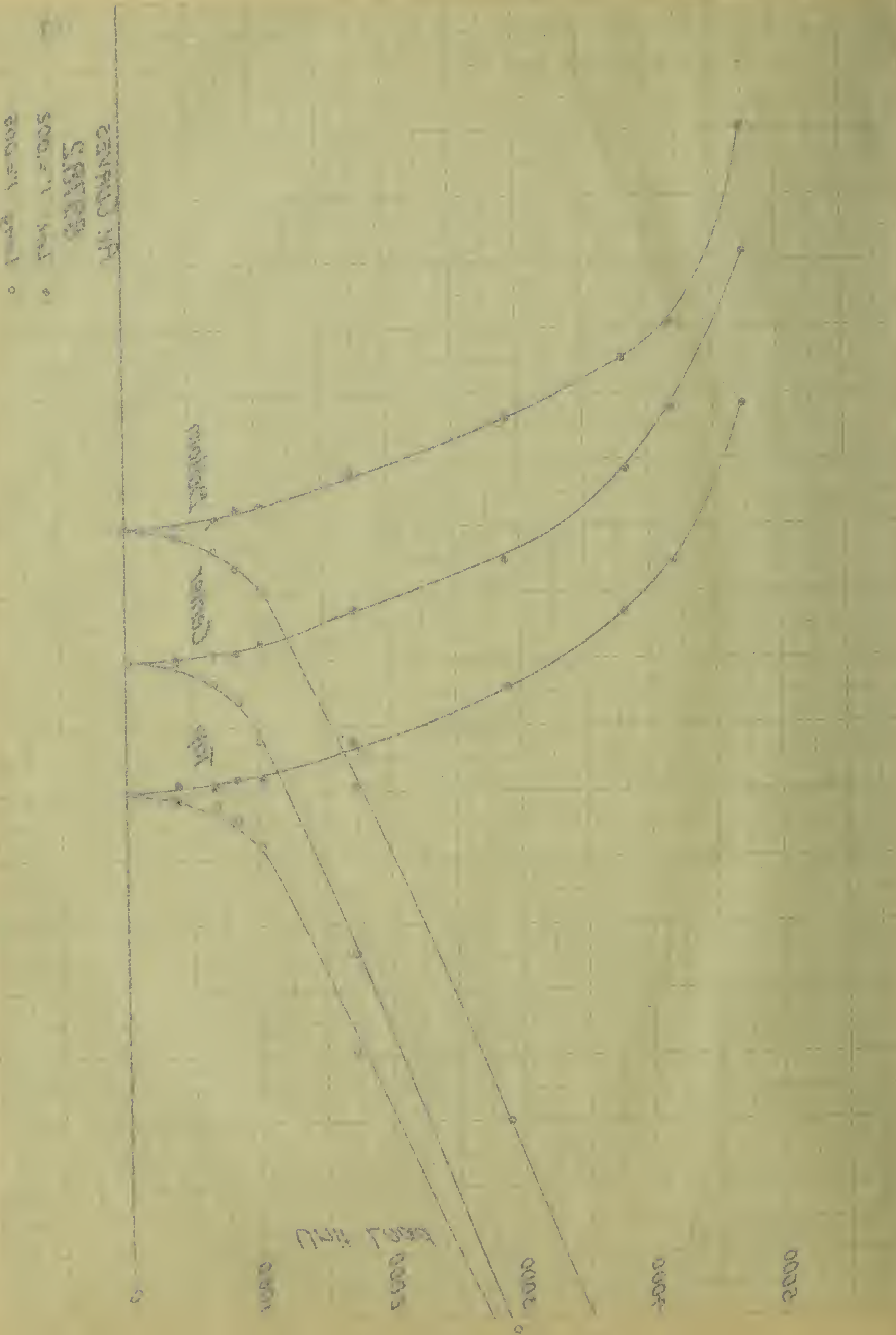

3000
2000
1000
0
Unit Load
Top
Center
Bottom
Av. CURVES
8977.2
2000
1000
0
Unit Load
Top
Center
Bottom
Av. CURVES
8977.1
• Lat. 1"=.002
○ Long. 1"=.005
94

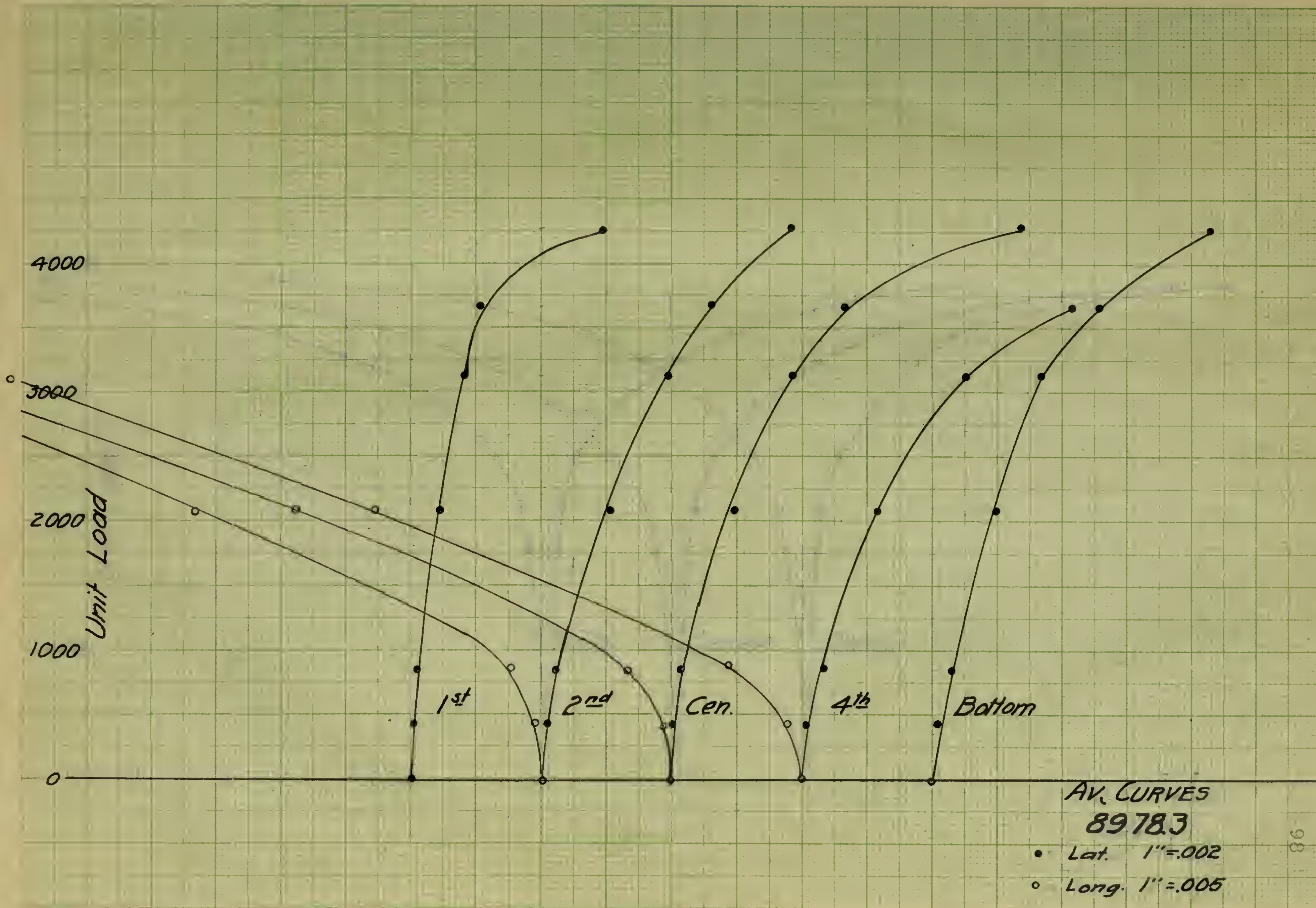

3000
2000
1000
0
Unit Load
Top
2nd
Center
4th
Bottom
AV. CURVES
8977.3
• Lat. 1" = .002
○ Long. 1" = .005

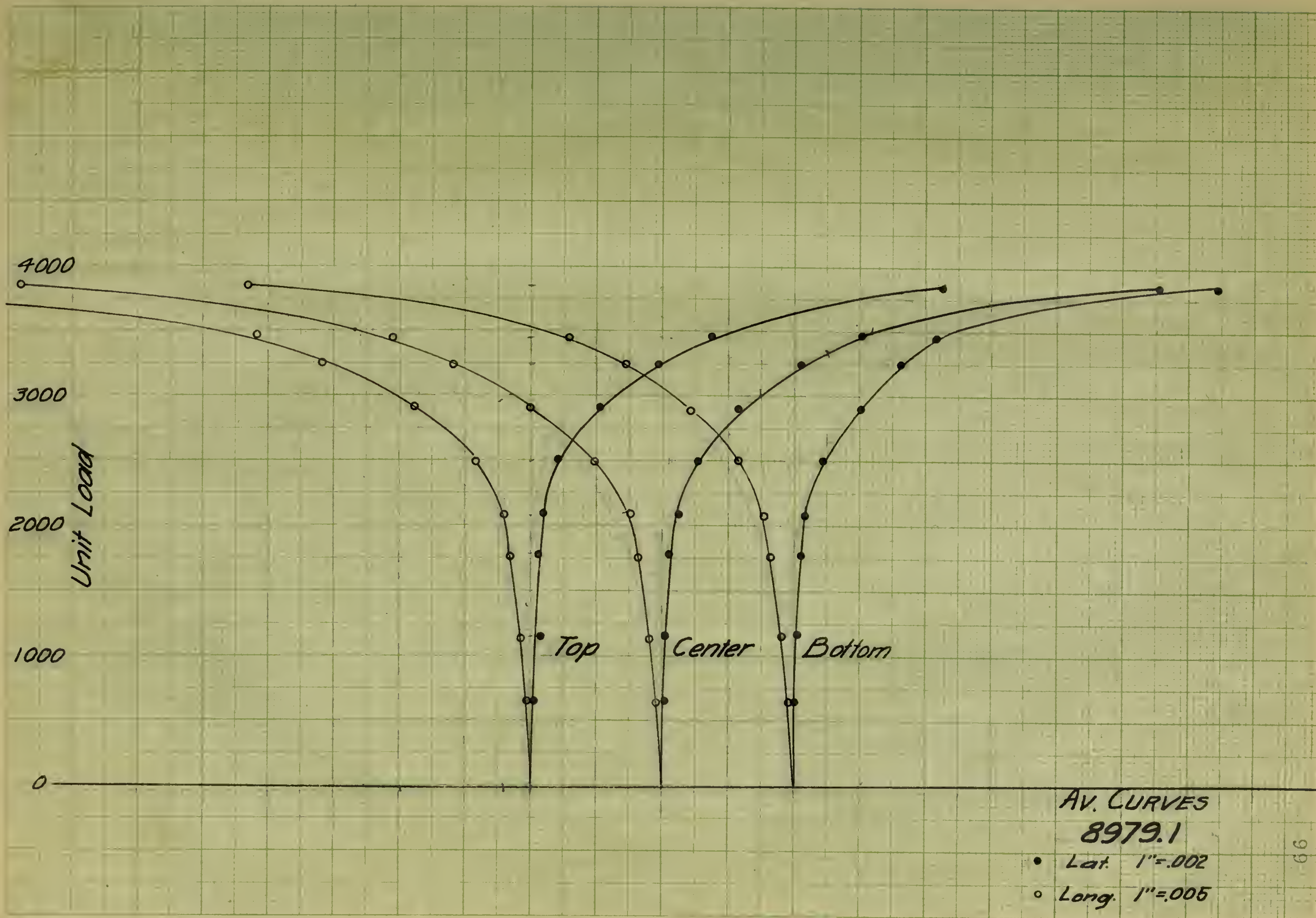


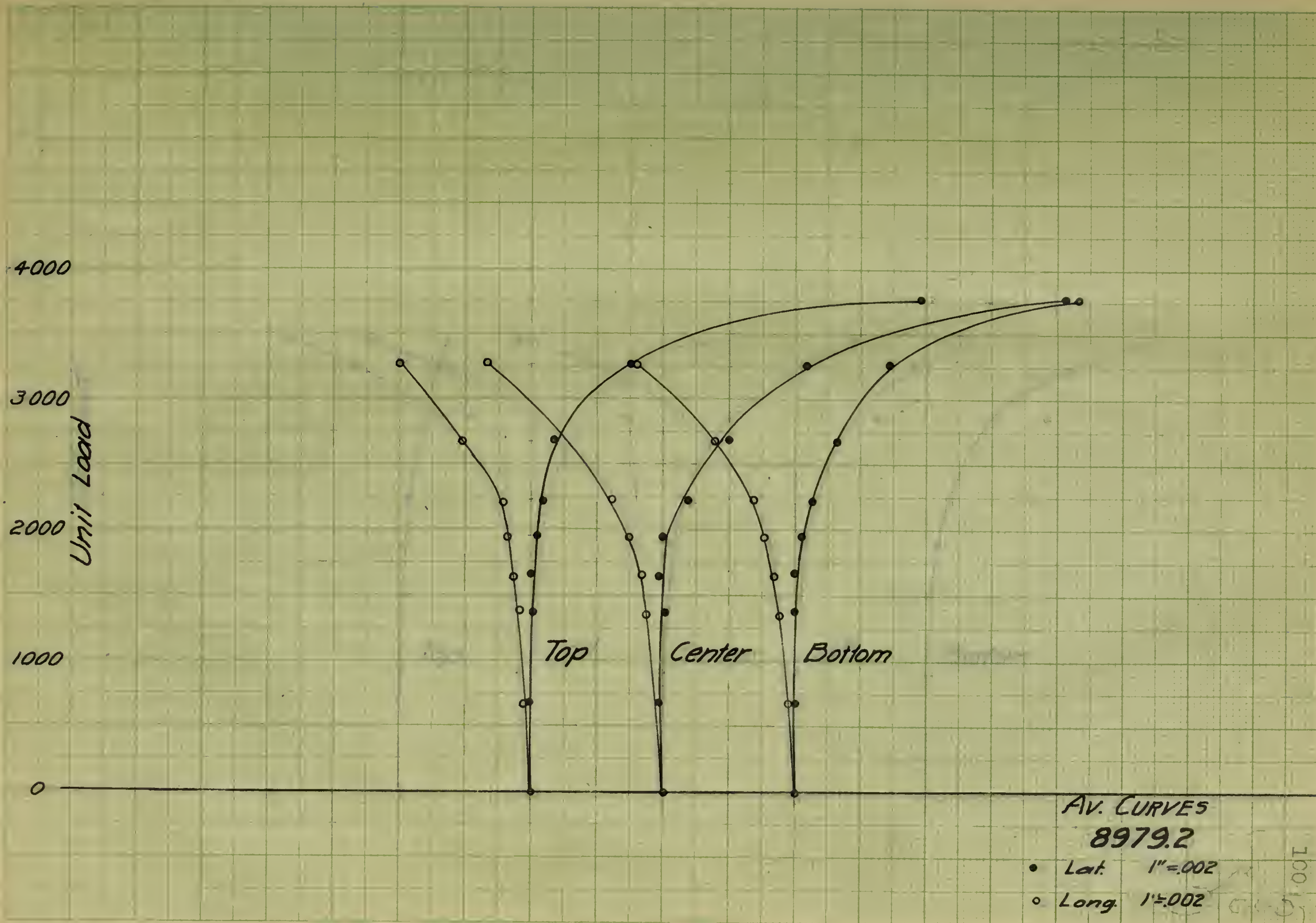

Unit Load
5000
4000
3000
2000
1000
0
Top
Center
Bottom
Av. CURVES
8978.1
Lat. 1"=.002
Long. 1"=.005

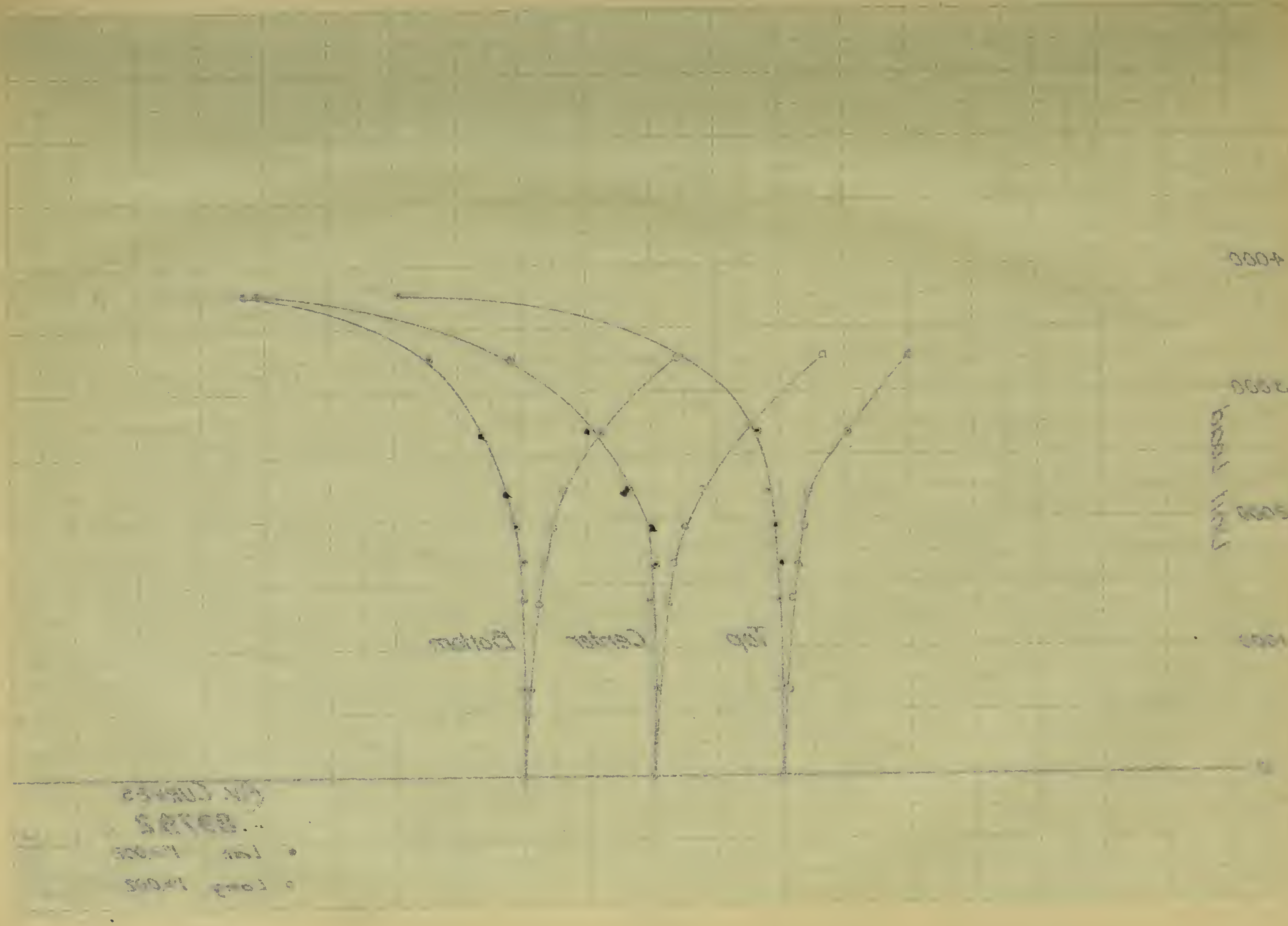

5000
4000
3000
2000
1000
0
Unit Load
Top
Center
Bottom
Av. Curves
8978.2
Lat. 1"=.002
Long. 1"=.005

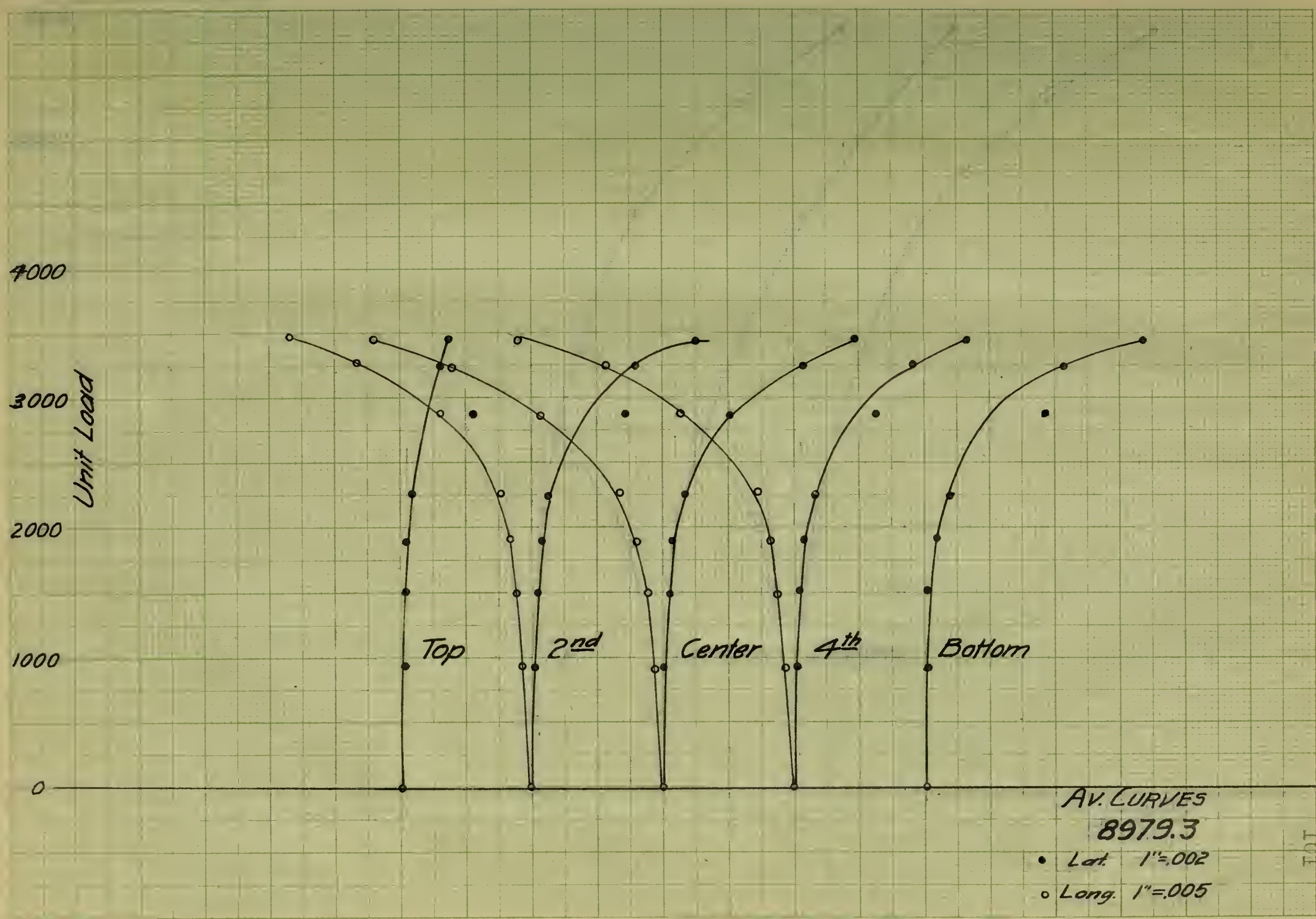


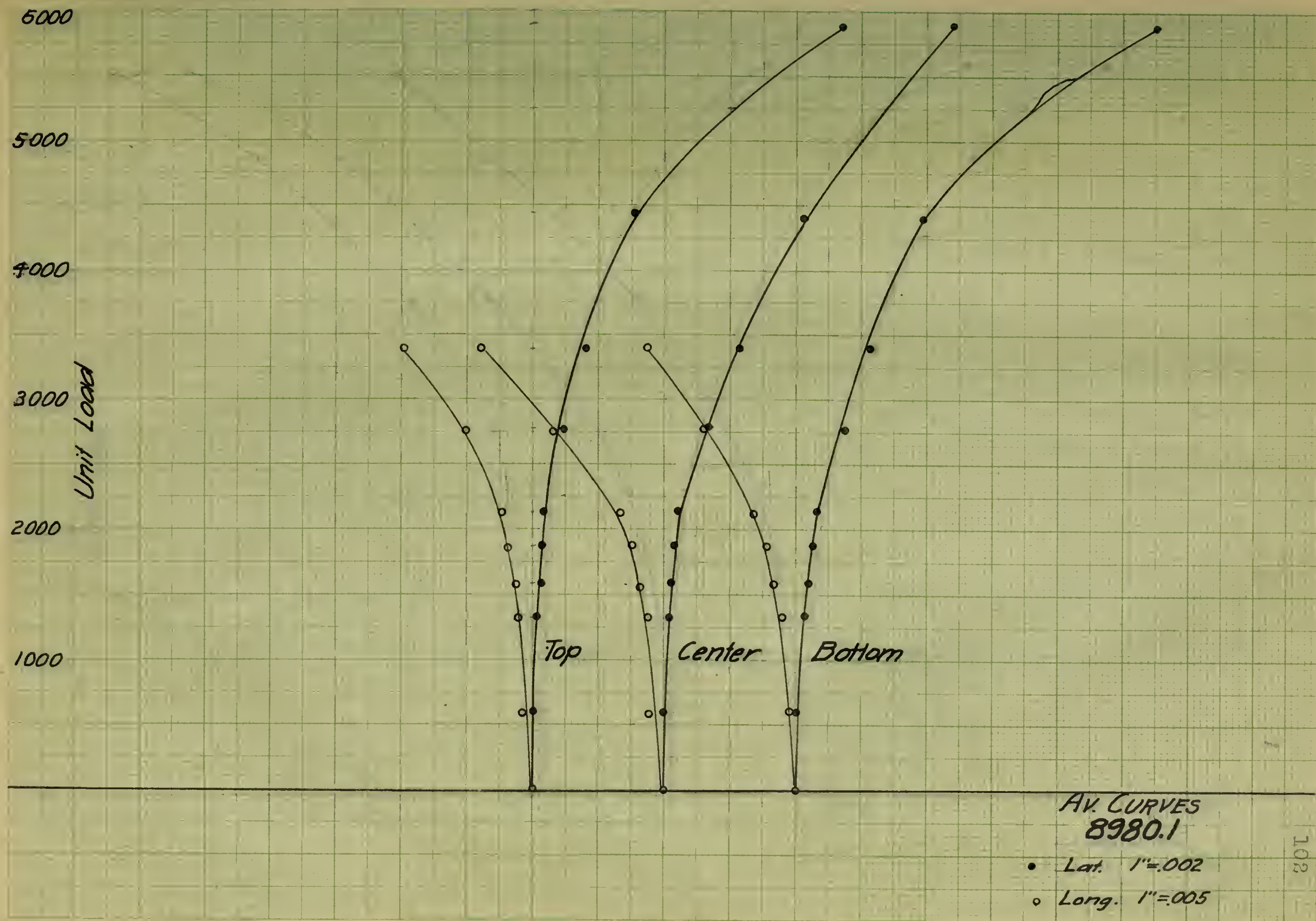

Unit Load
4000
3000
2000
1000
0
1st
2nd
Cen.
4th
Bottom
Av. CURVES
8978.3
Lat. 1" = .002
Long. 1" = .005

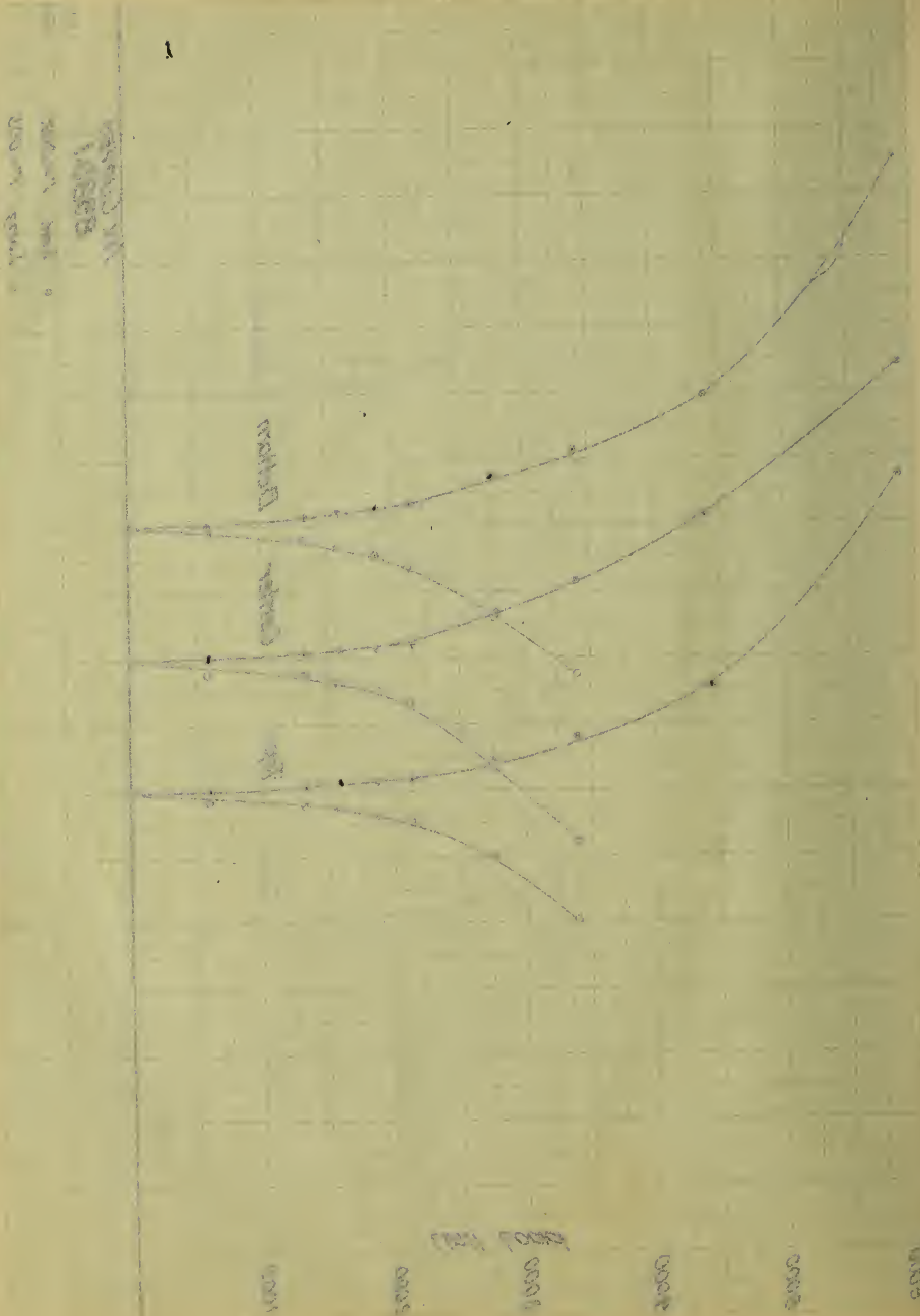

4000
3000
2000
1000
0
Unit Load
Top
Center
Bottom
Av. Curves
8979.1
Lat. 1"=.002
Long. 1"=.005

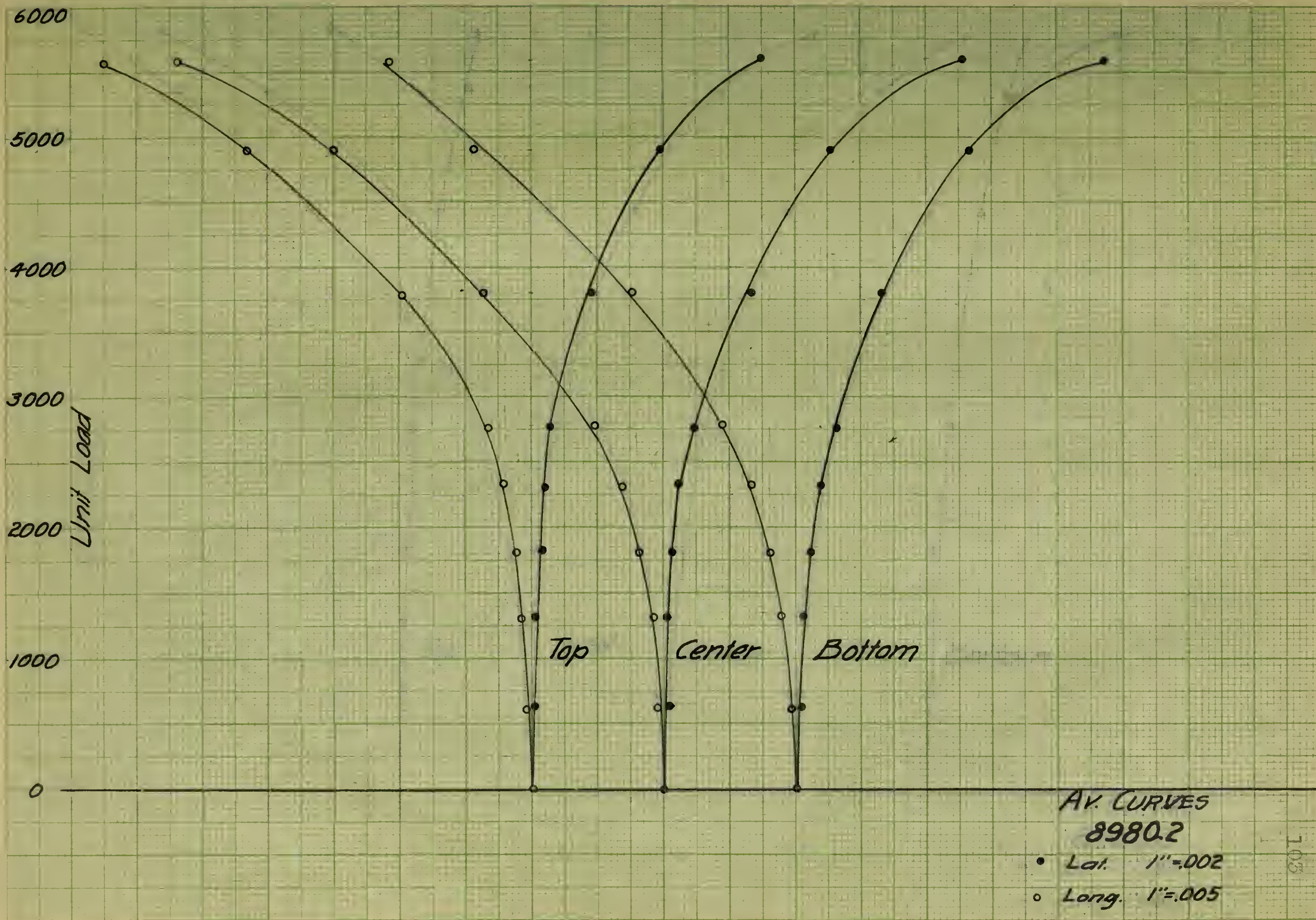

4000
3000
2000
1000
0
Unit Load
Top
Center
Bottom
Av. CURVES
8979.2
Lat. 1"=.002
Long. 1"=.002

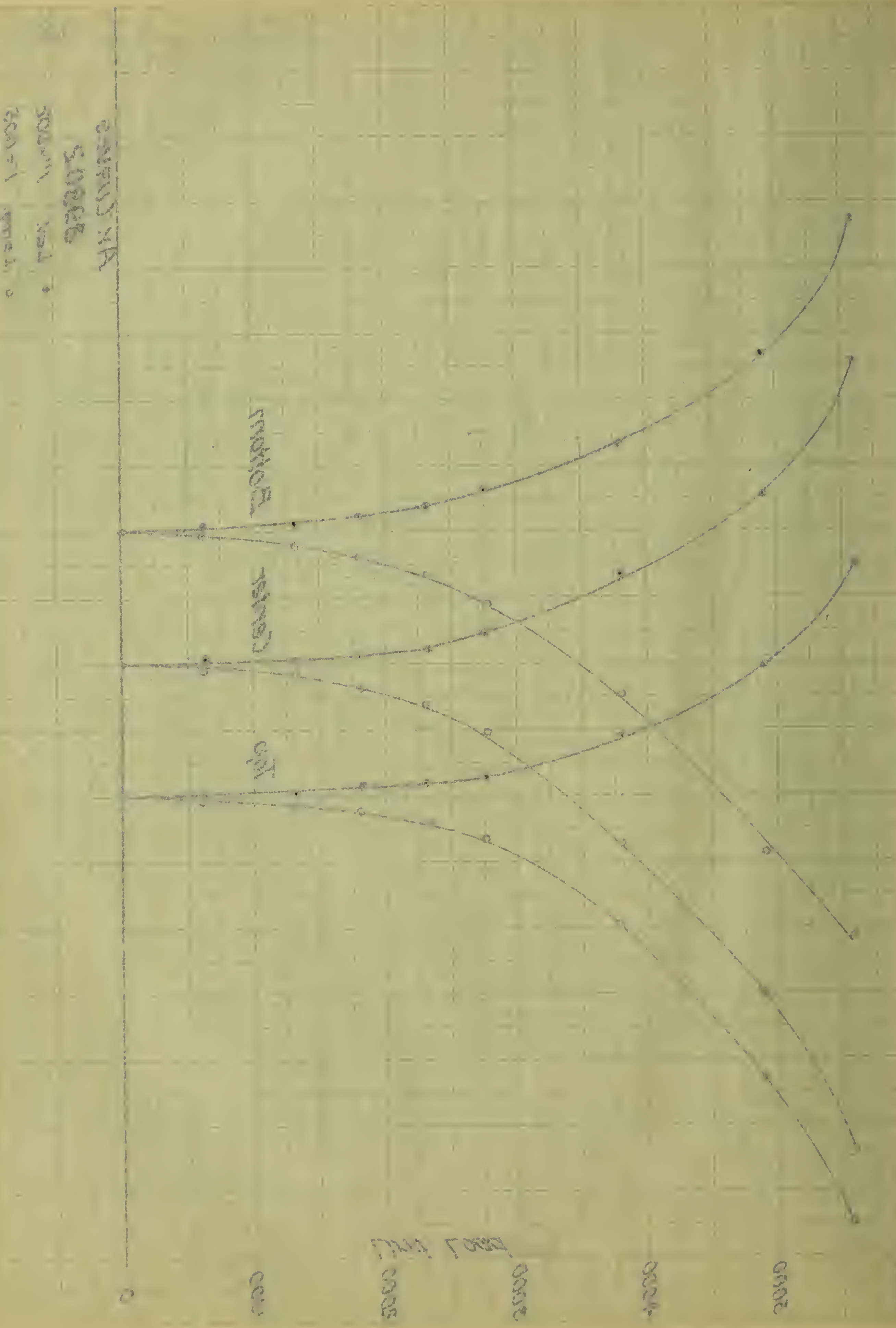


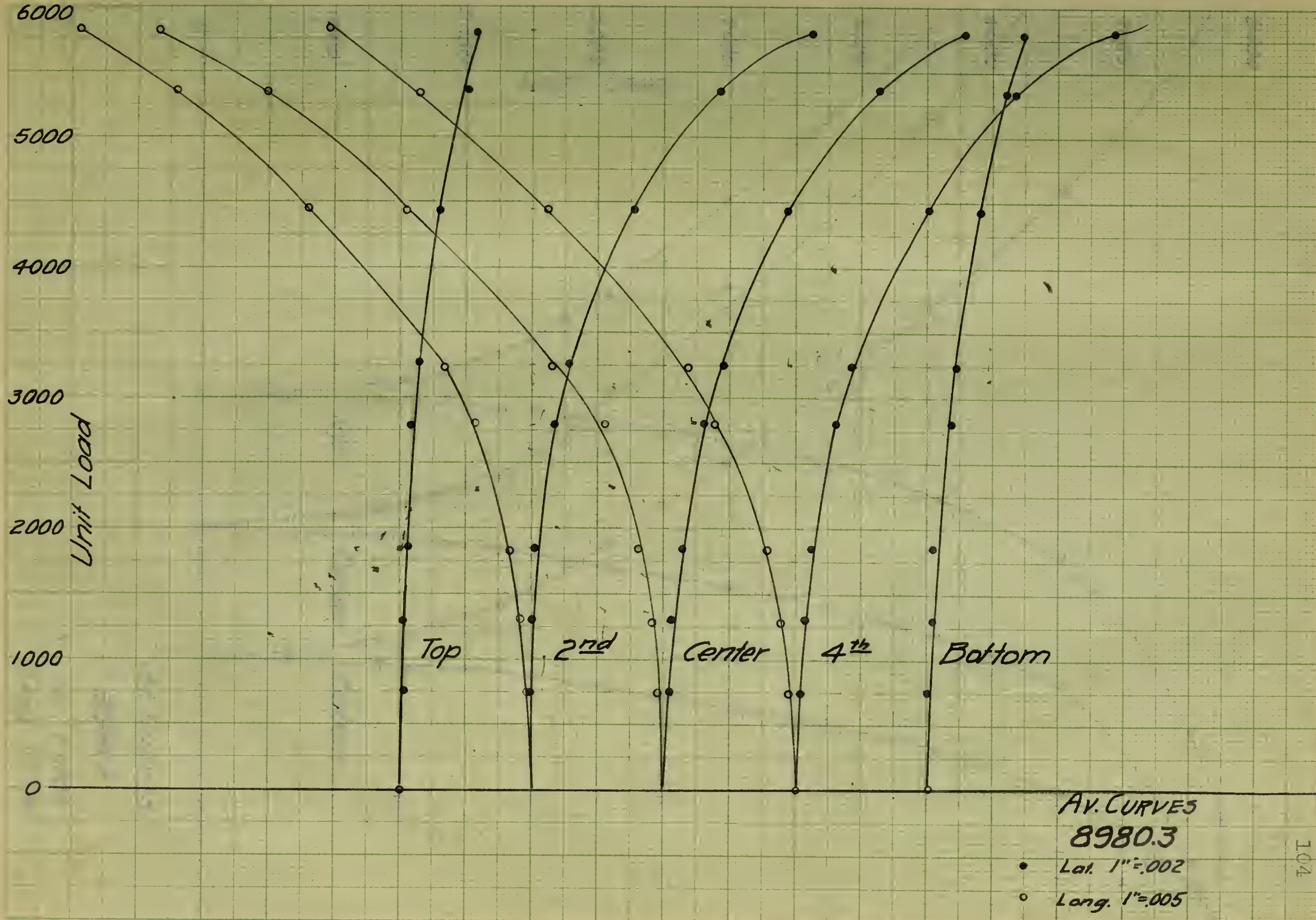

4000
3000
2000
1000
0
Unit Load
Top
2nd
Center
4th
Bottom
Av. CURVES
8979.3
Lat. 1"=.002
Long. 1"=.005

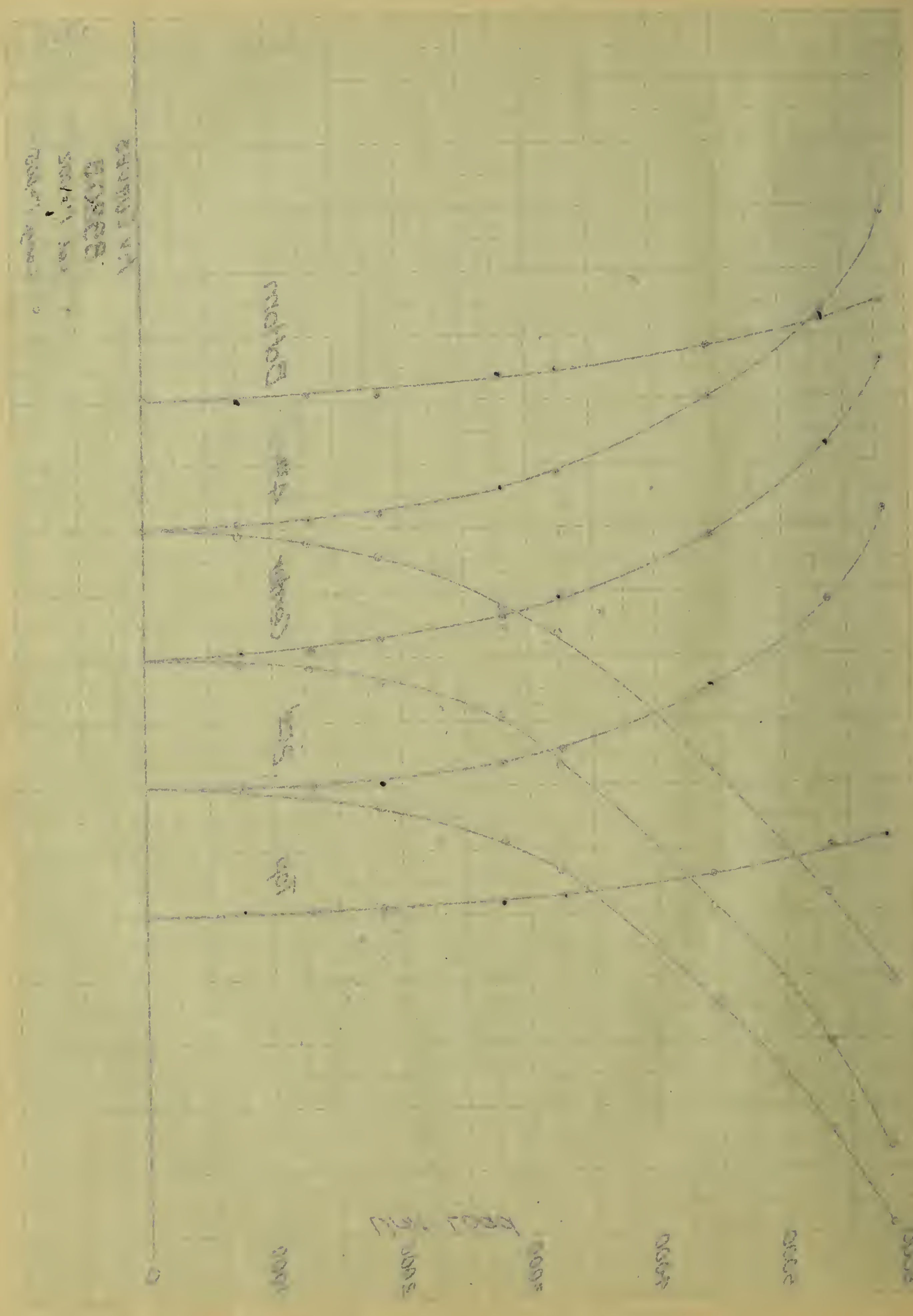

6000
5000
4000
3000
2000
1000
Unit Load
Top
Center
Bottom
Av. CURVES
8980.1
• Lat. 1"=.002
∘ Long. 1"=.005

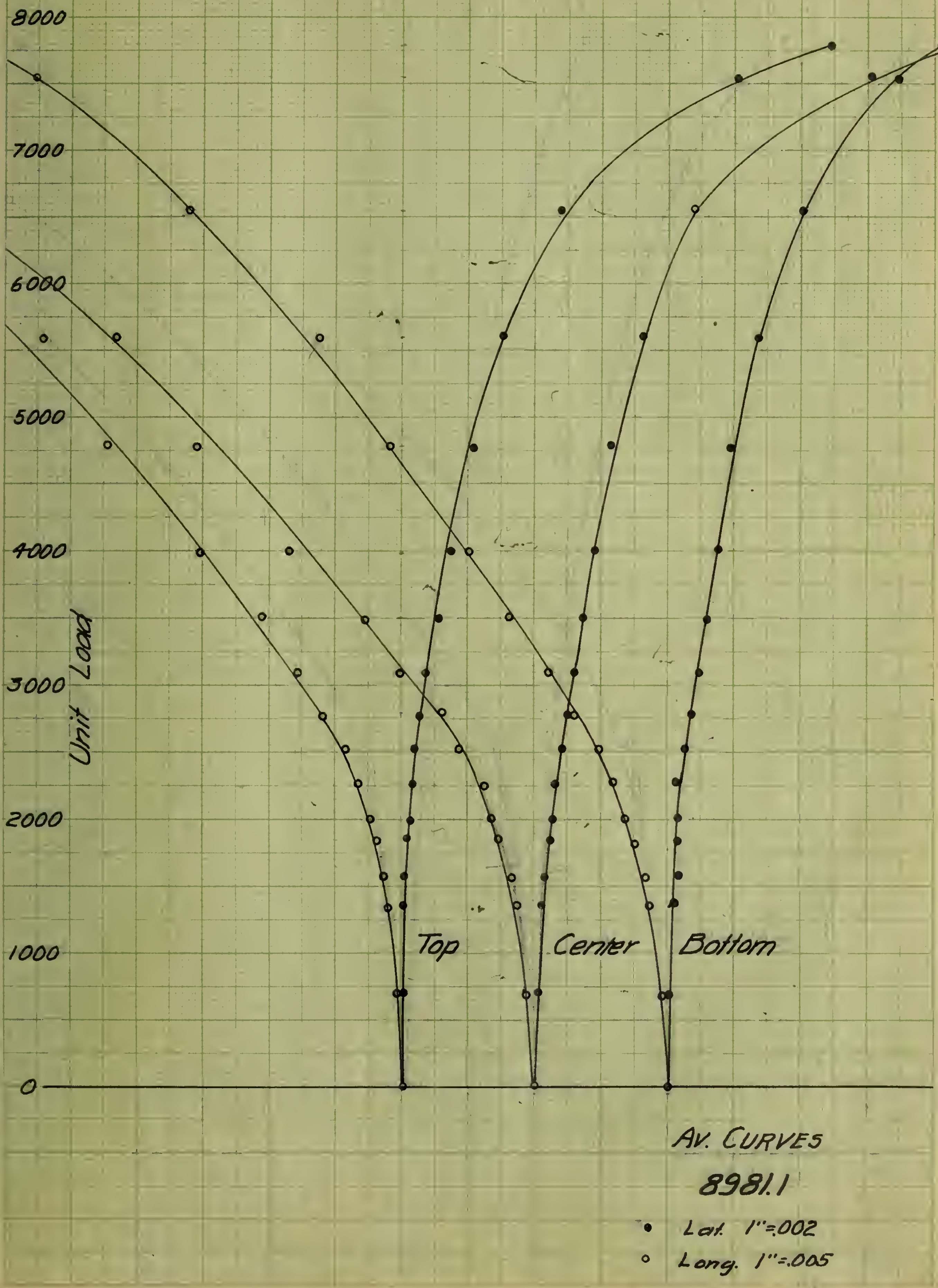


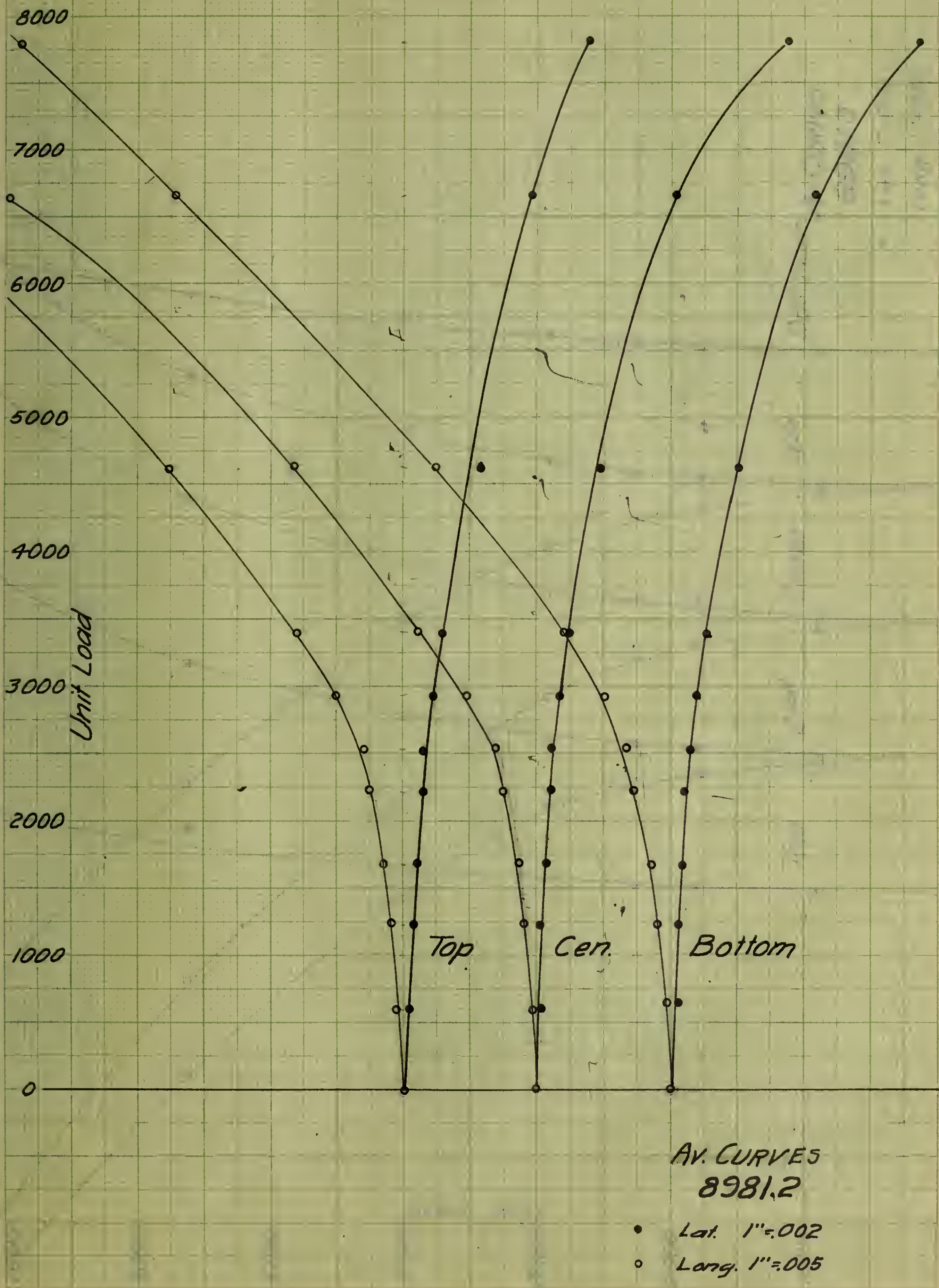

6000
5000
4000
3000
2000
1000
0
Unit Load
Top
Center
Bottom
Av. Curves
8980.2
• Lat. 1" = .002
○ Long. 1" = .005

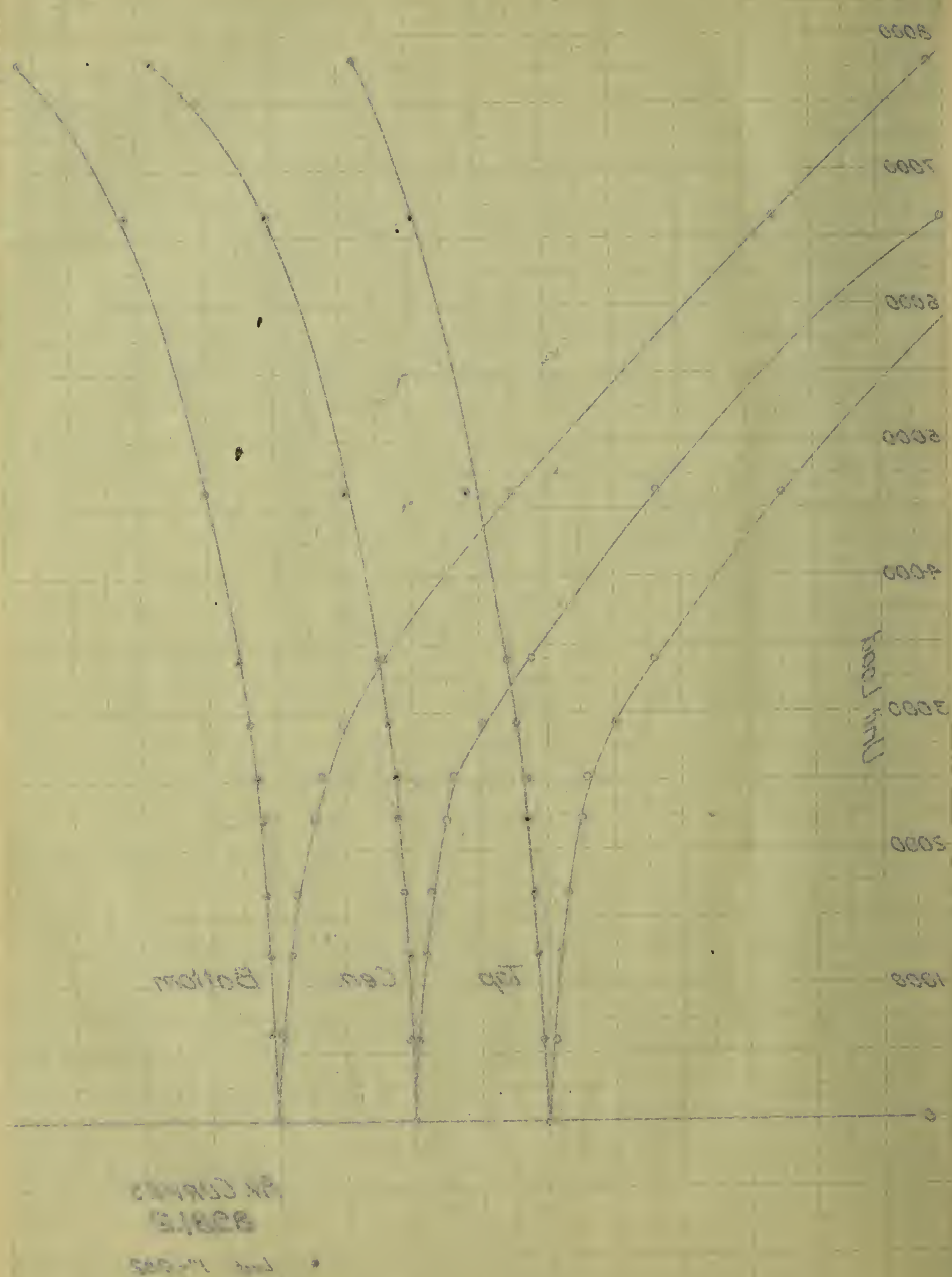


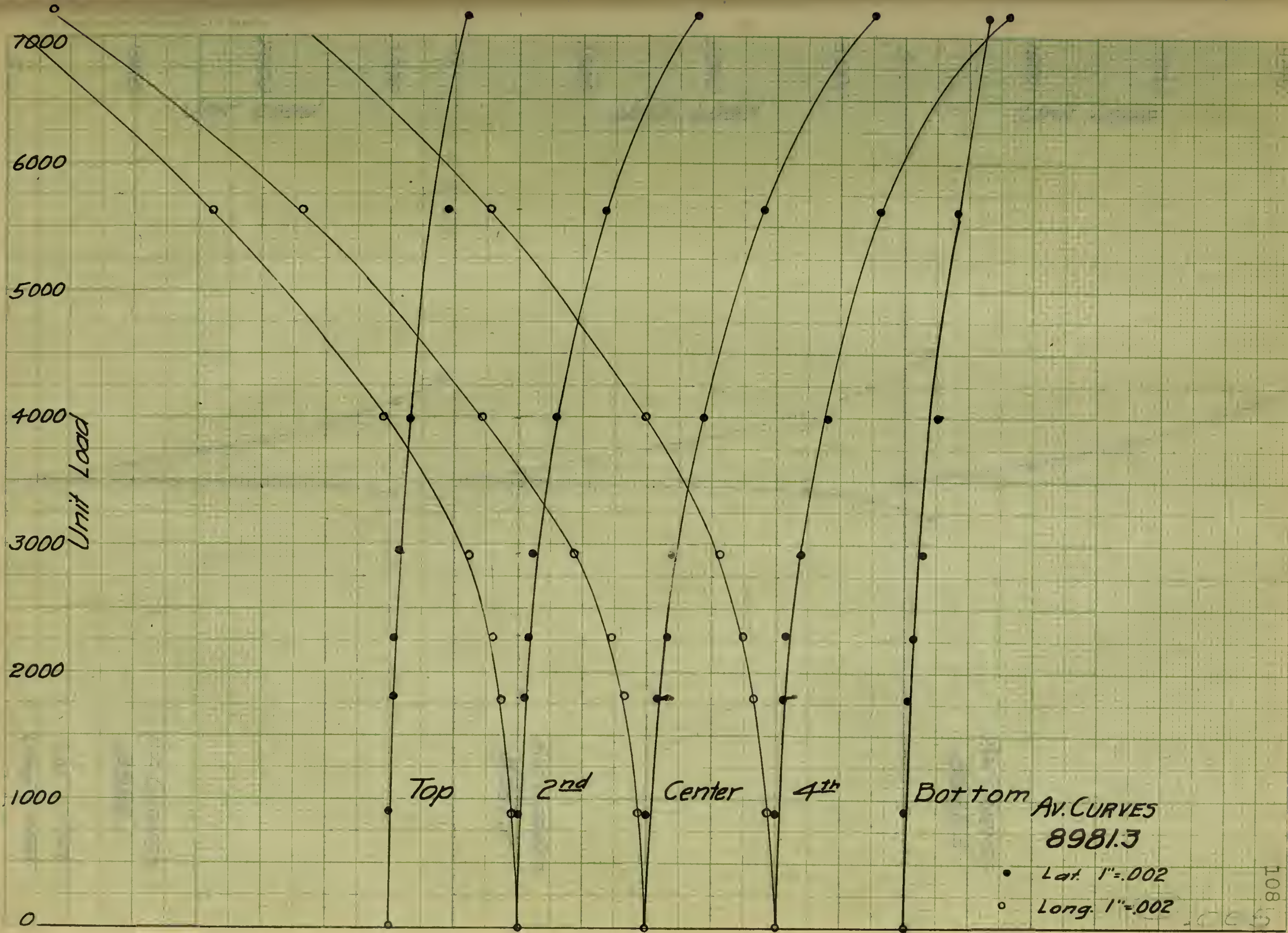

6000
5000
4000
3000
2000
1000
0
Unit Load
Top
2nd
Center
4th
Bottom
Av. CURVES
8980.3
Lat. 1"=.002
Long. 1"=.005
104



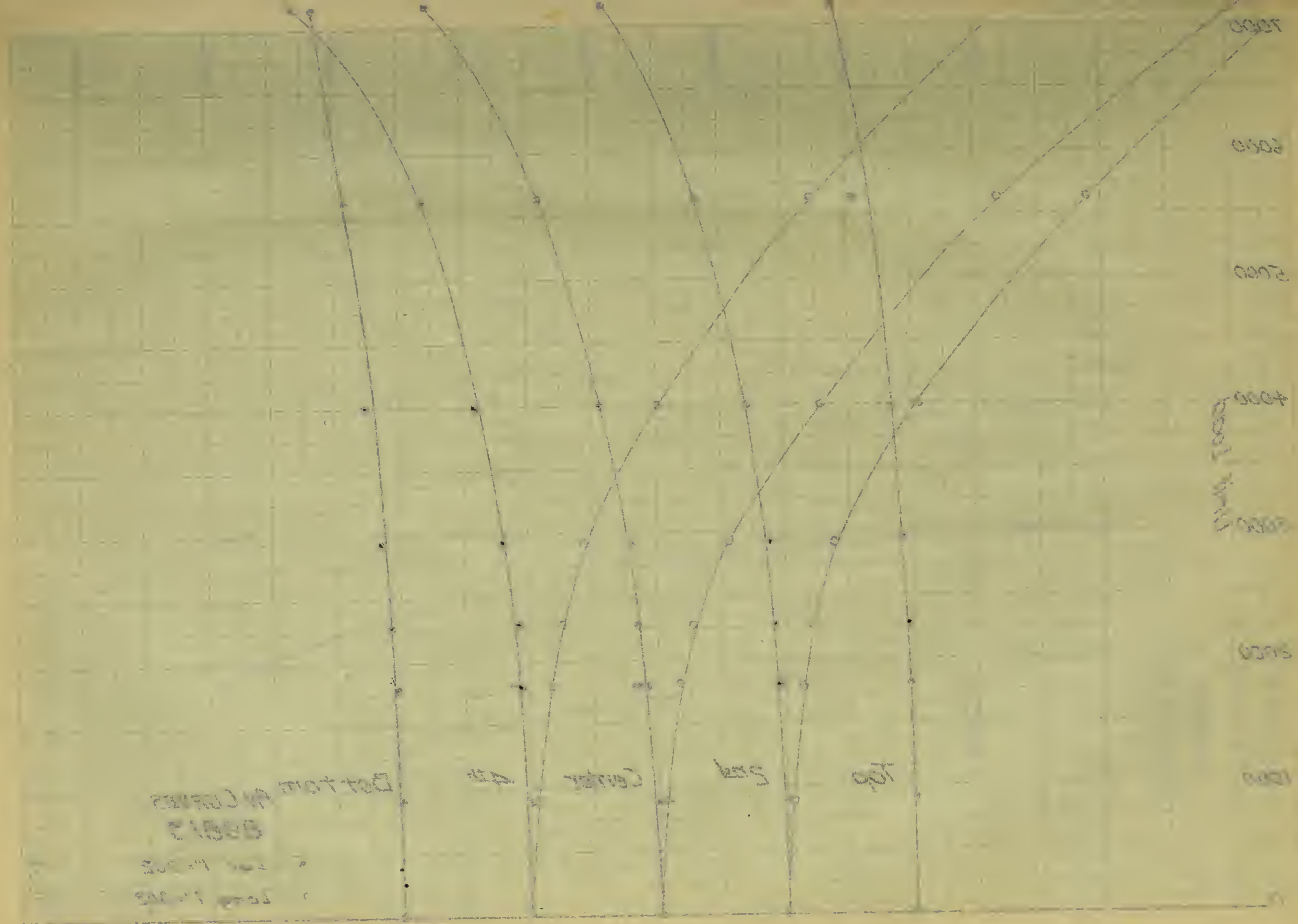

8000
7000
6000
5000
4000
3000
2000
1000
0
Unit Load
Top
Center
Bottom
Av. Curves
8981.1
Lat. 1"=.002
Long. 1"=.005


8000
7000
6000
5000
4000
3000
2000
1000
0
Unit Load
Top
Cen.
Bottom
Av. CURVES
8981.2
Lat. 1" = .002
Long. 1" = .005

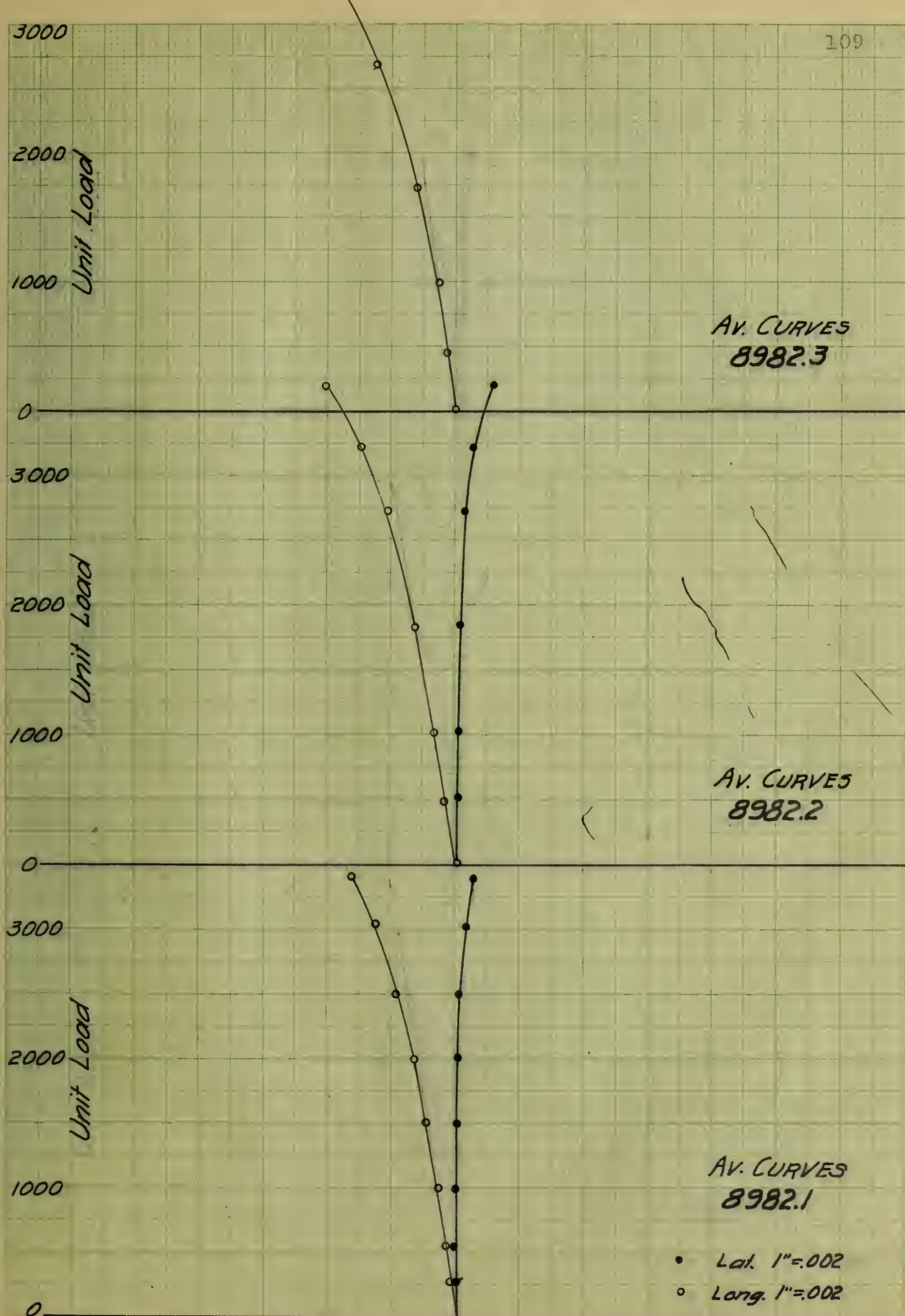


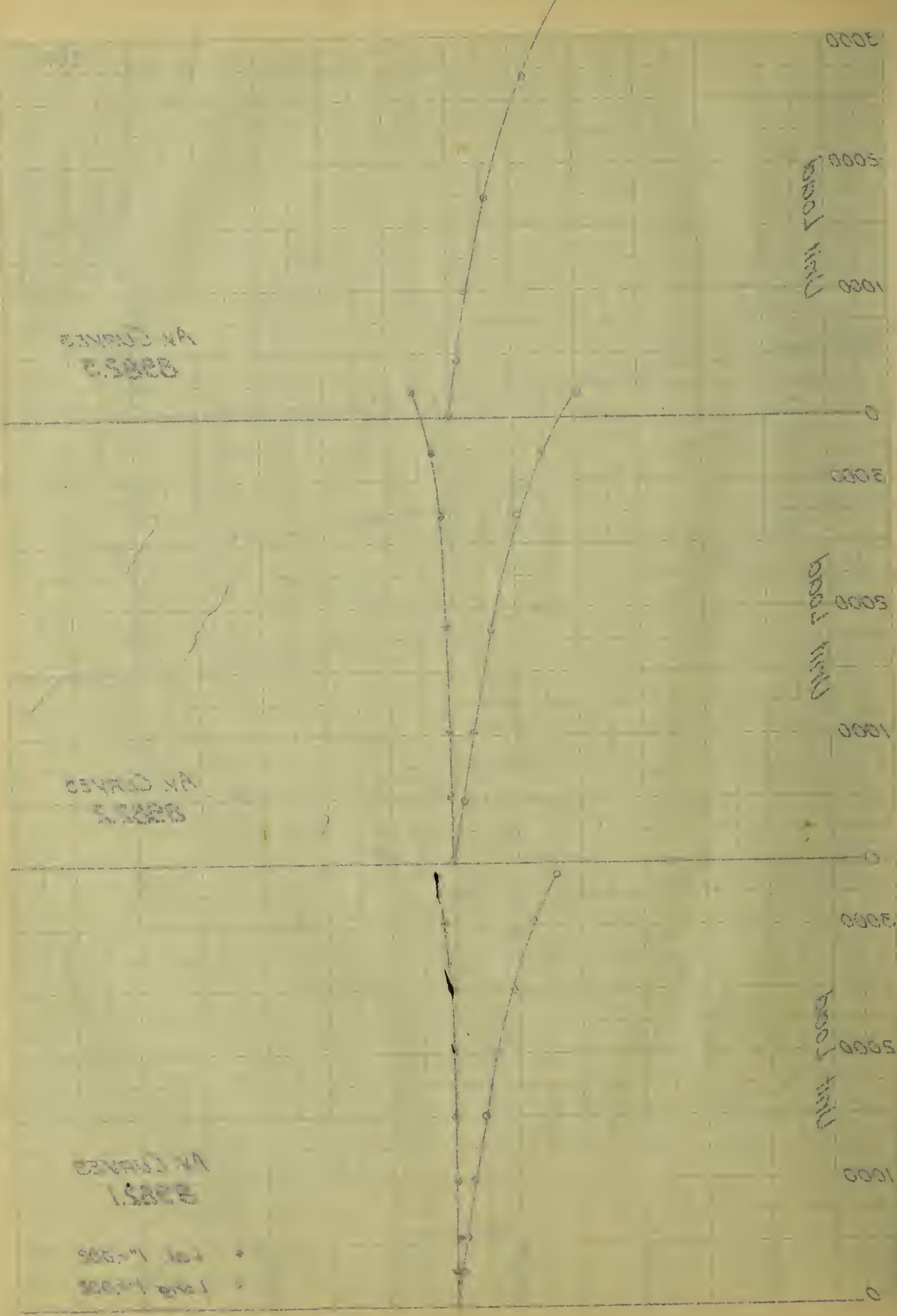


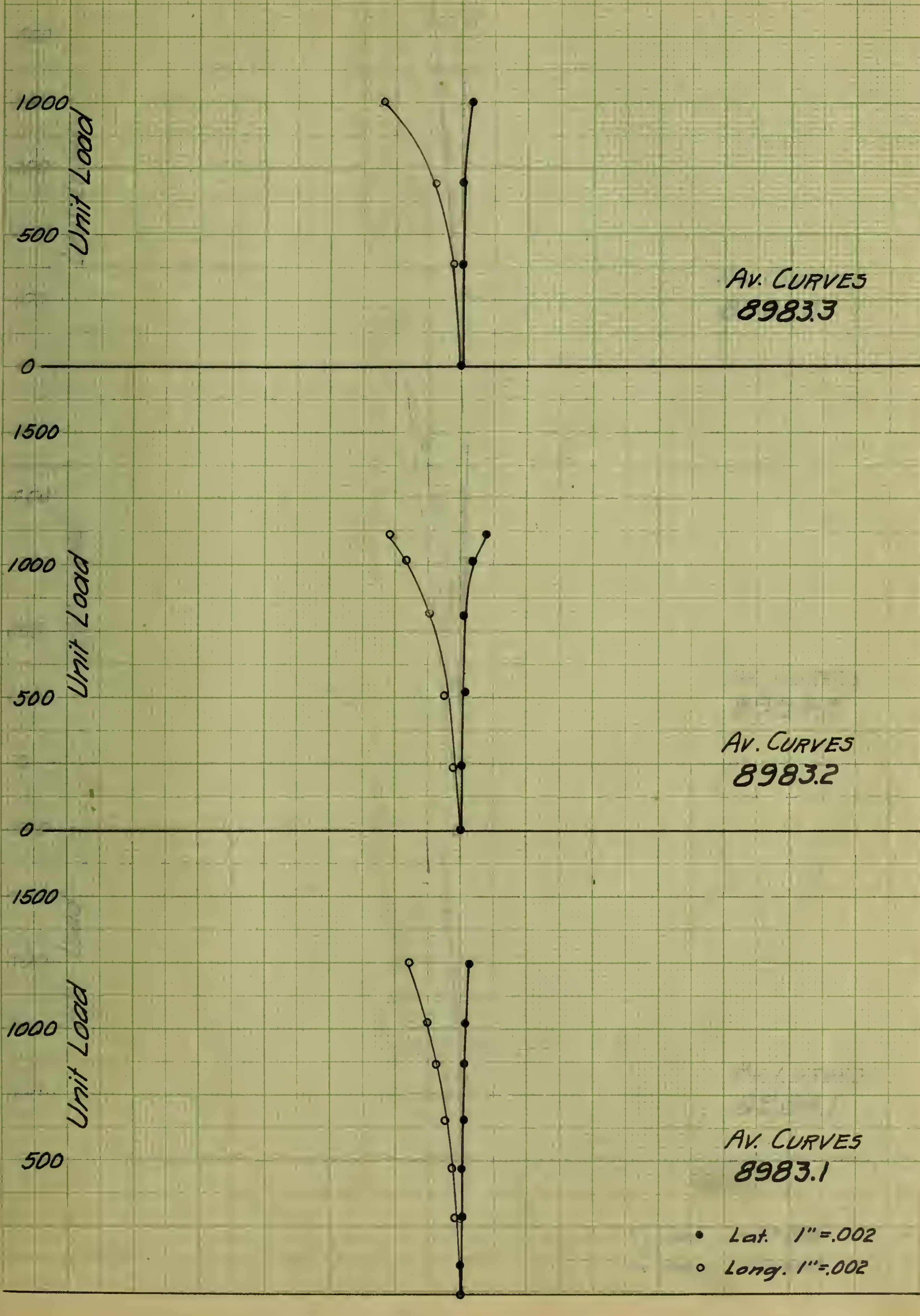
Unit Load
0
1000
2000
3000
4000
5000
6000
7000
Top
2nd
Center
4th
Bottom
Av. CURVES
8981.3
Lat. 1" = .002
Long. 1" = .002



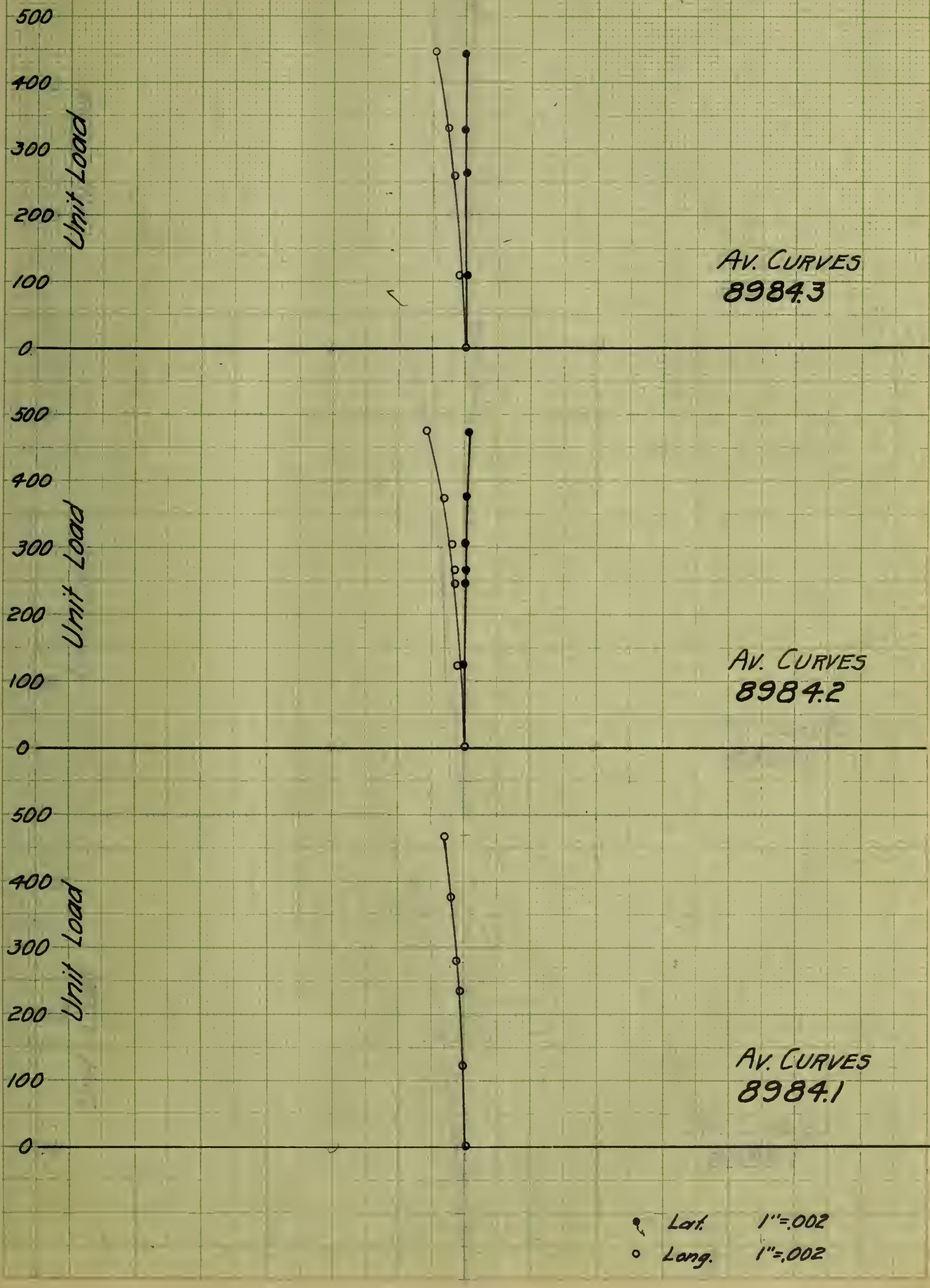
Top
2nd
Center
4th
Bottom 4 Corners
1000
2000
3000
4000
5000
6000
7000


3000
2000
1000
0
Unit Load
Av. Curves
8982.3
3000
2000
1000
0
Unit Load
Av. Curves
8982.2
3000
2000
1000
0
Unit Load
Av. Curves
8982.1
• Lat. 1"=.002
○ Long. 1"=.002

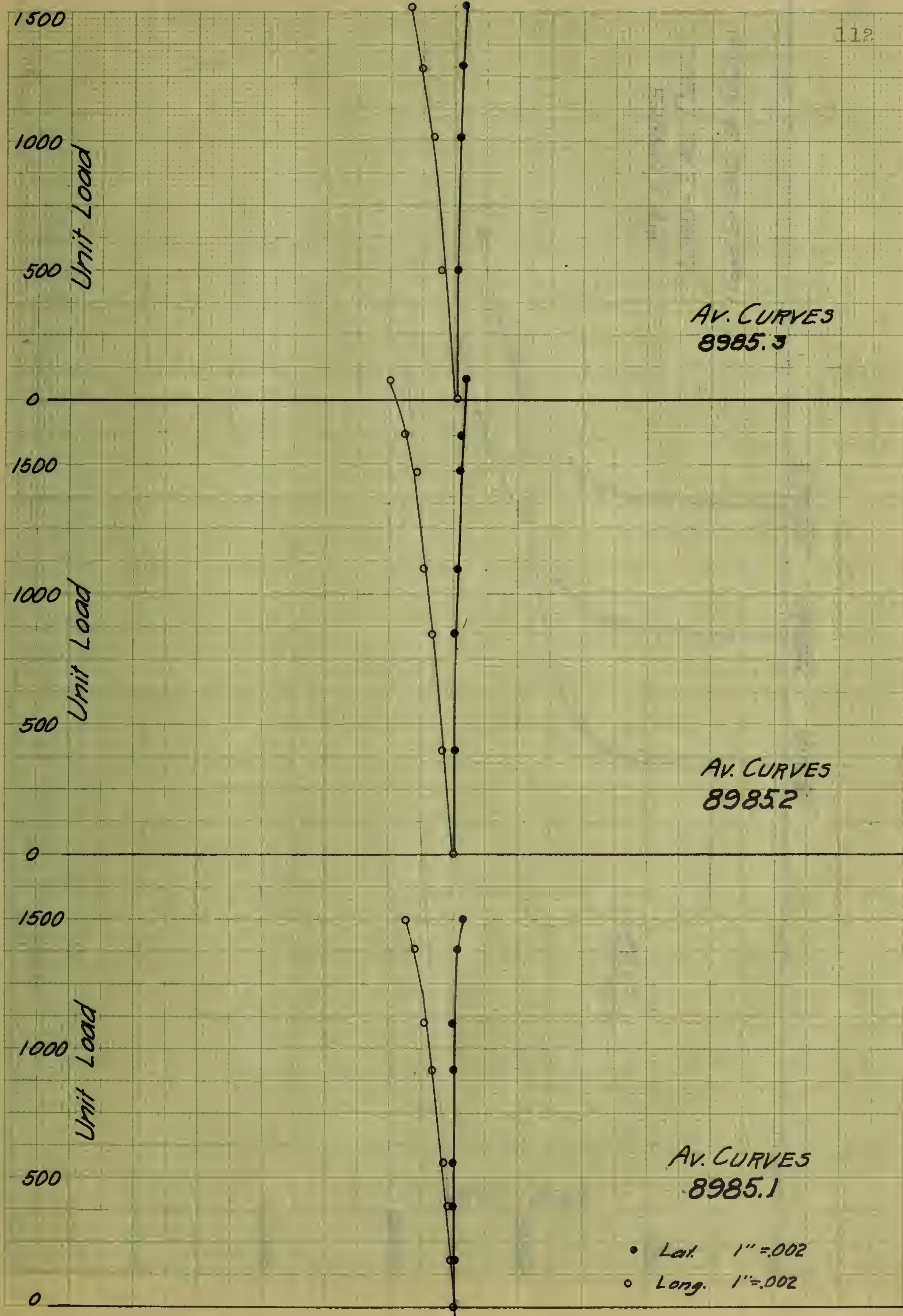


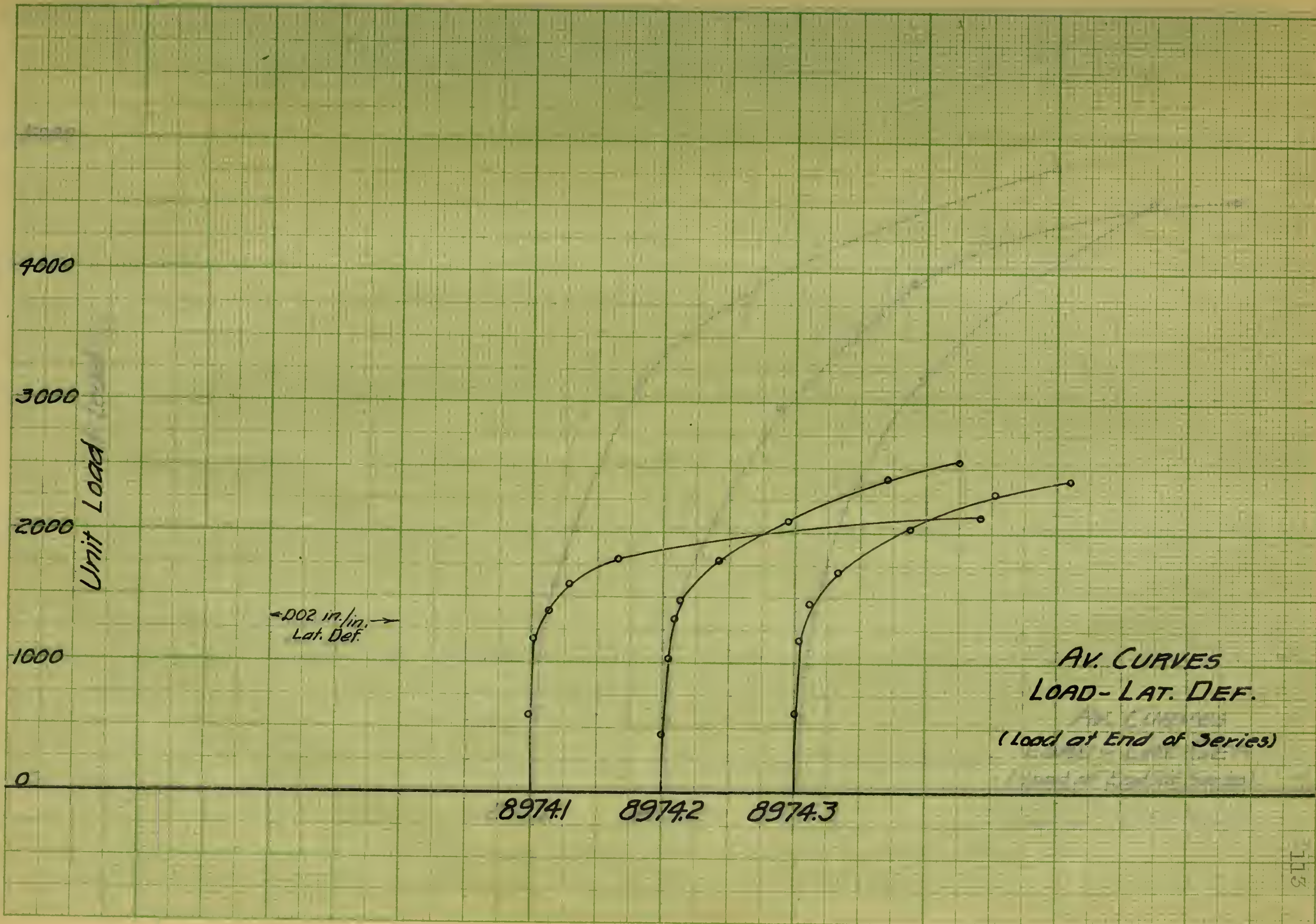


1000
500
0
Unit Load
Av. Curves
8983.3
1500
1000
500
0
Unit Load
Av. Curves
8983.2
1500
1000
500
Unit Load
Av. Curves
8983.1
• Lat. 1" = .002
o Long. 1" = .002

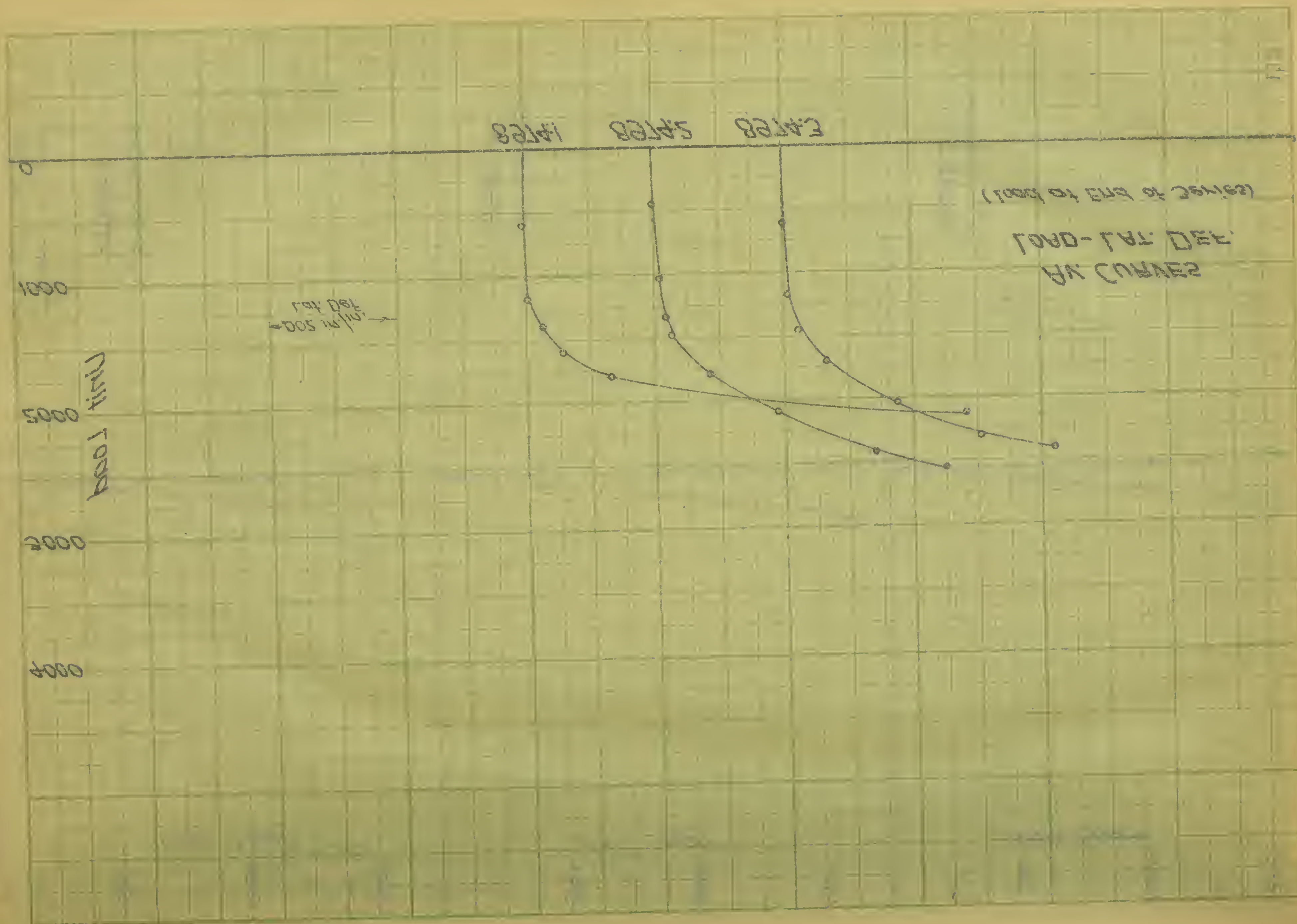


500
400
300
200
100
0
Unit Load
Av. Curves
8984.3
500
400
300
200
100
0
Unit Load
Av. Curves
8984.2
500
400
300
200
100
0
Unit Load
Av. Curves
8984.1
Lat. 1"=.002
Long. 1"=.002

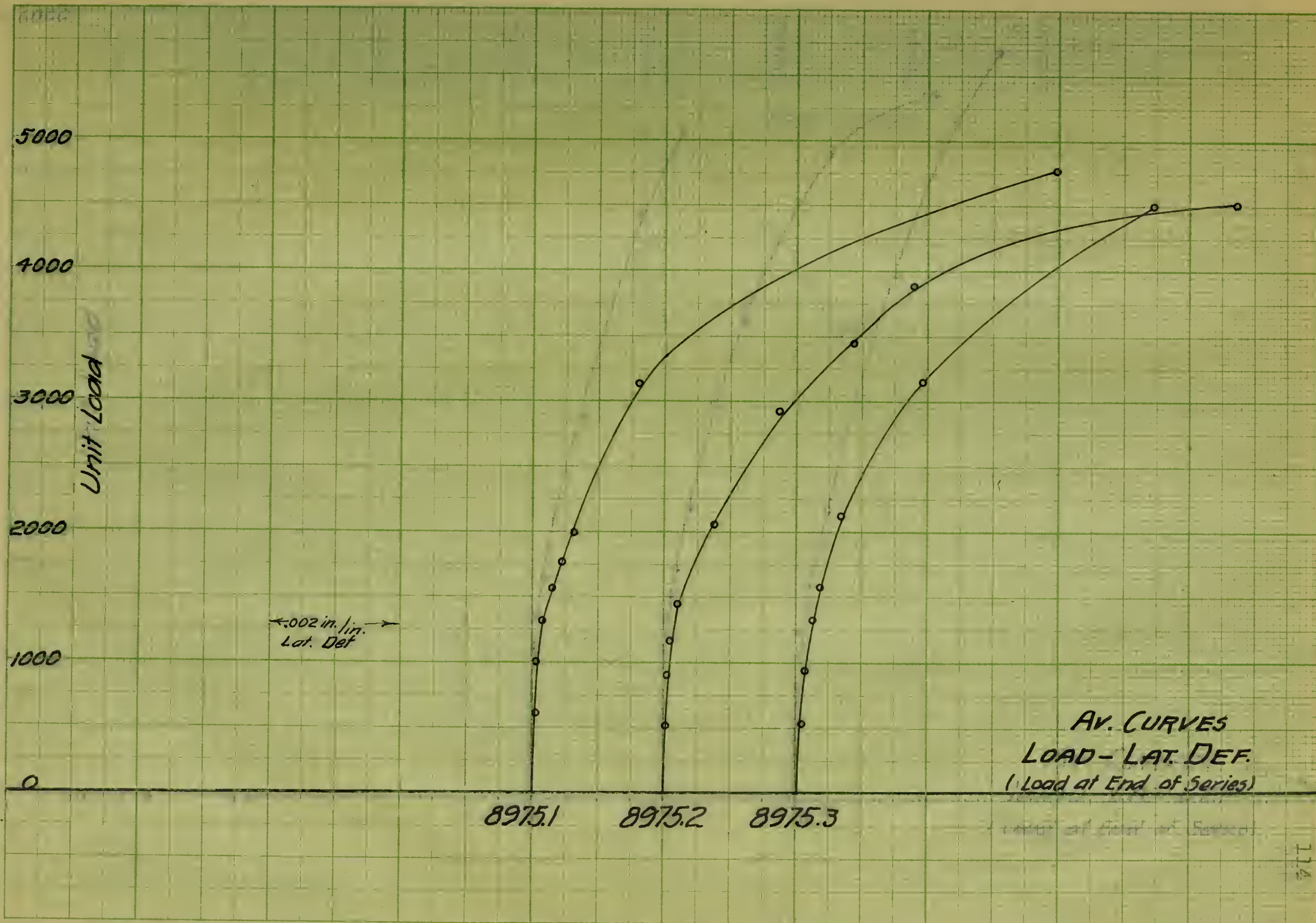

1500
1000
500
0
Unit Load
Av. Curves
8985.3
1500
1000
500
0
Unit Load
Av. Curves
8985.2
1500
1000
500
0
Unit Load
Av. Curves
8985.1
• Lat. 1" = .002
○ Long. 1" = .002

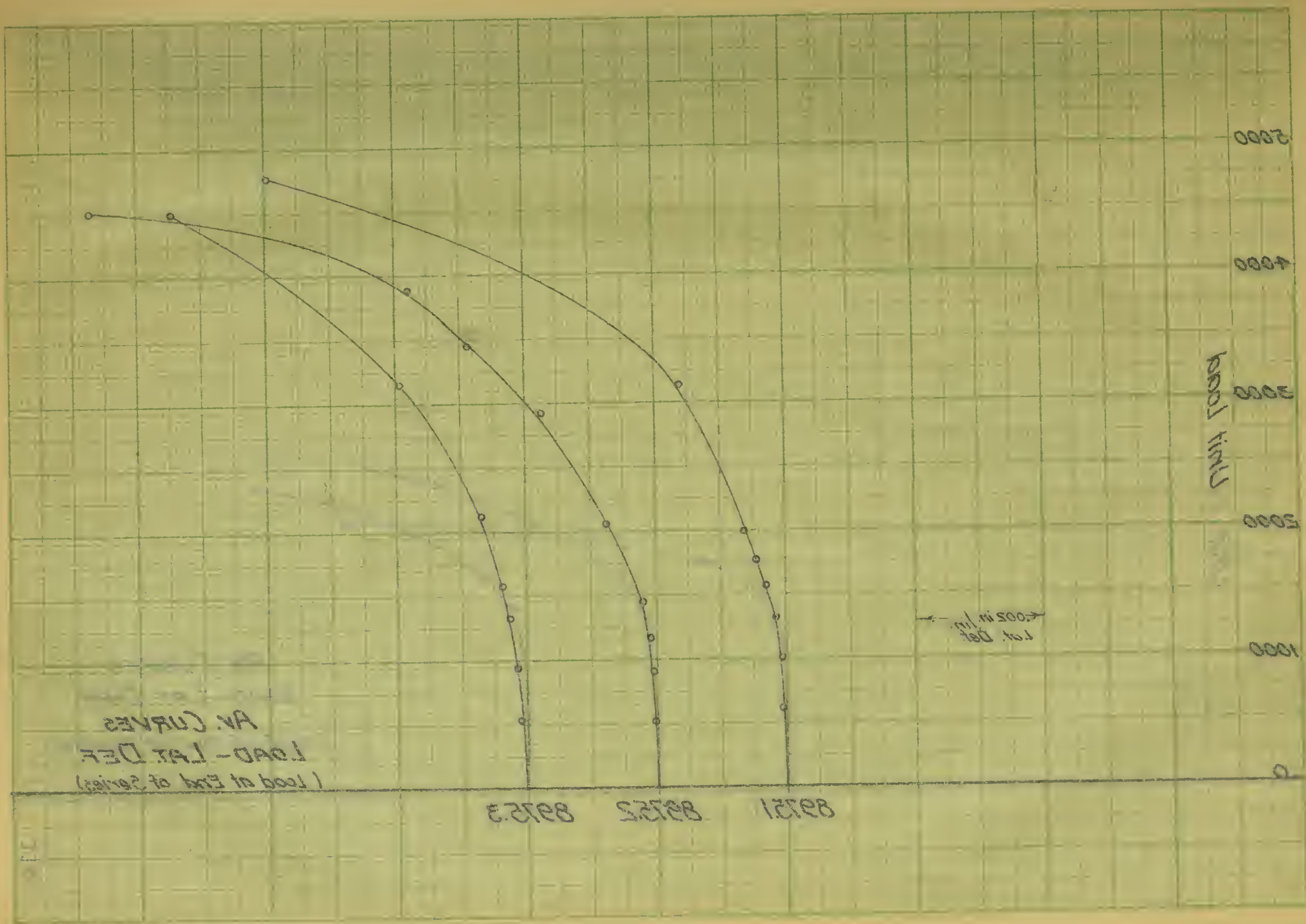


Av. Curves
Load - Lat. Def.
(Load at End of Series)
Unit Load
4000
3000
2000
1000
0
←.002 in./in.→
Lat. Def.
8974.1
8974.2
8974.3

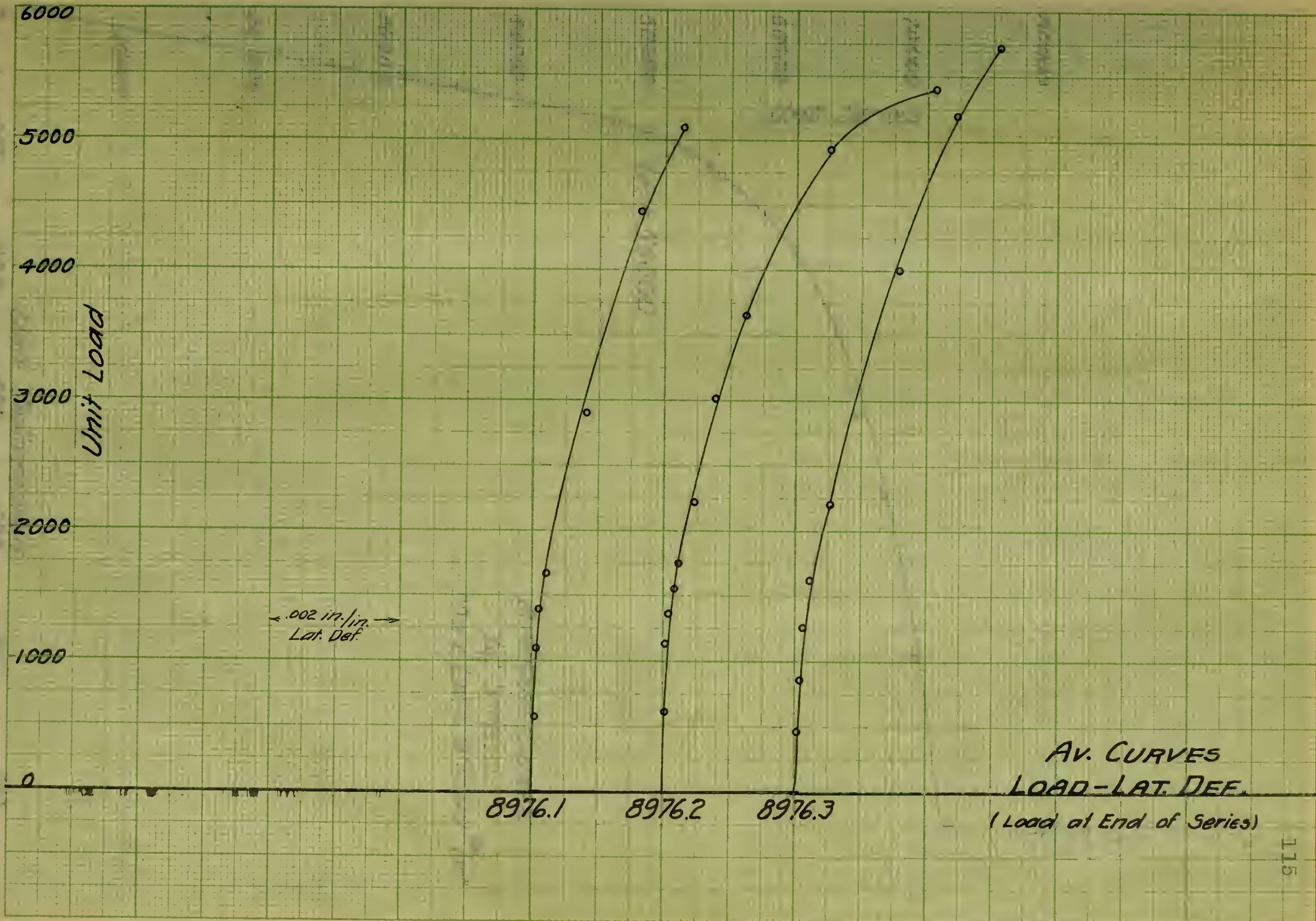


AV CURVES
LOAD - LAT. DEF.
(Load at End of Series)
Unit Load
0
1000
2000
3000
4000

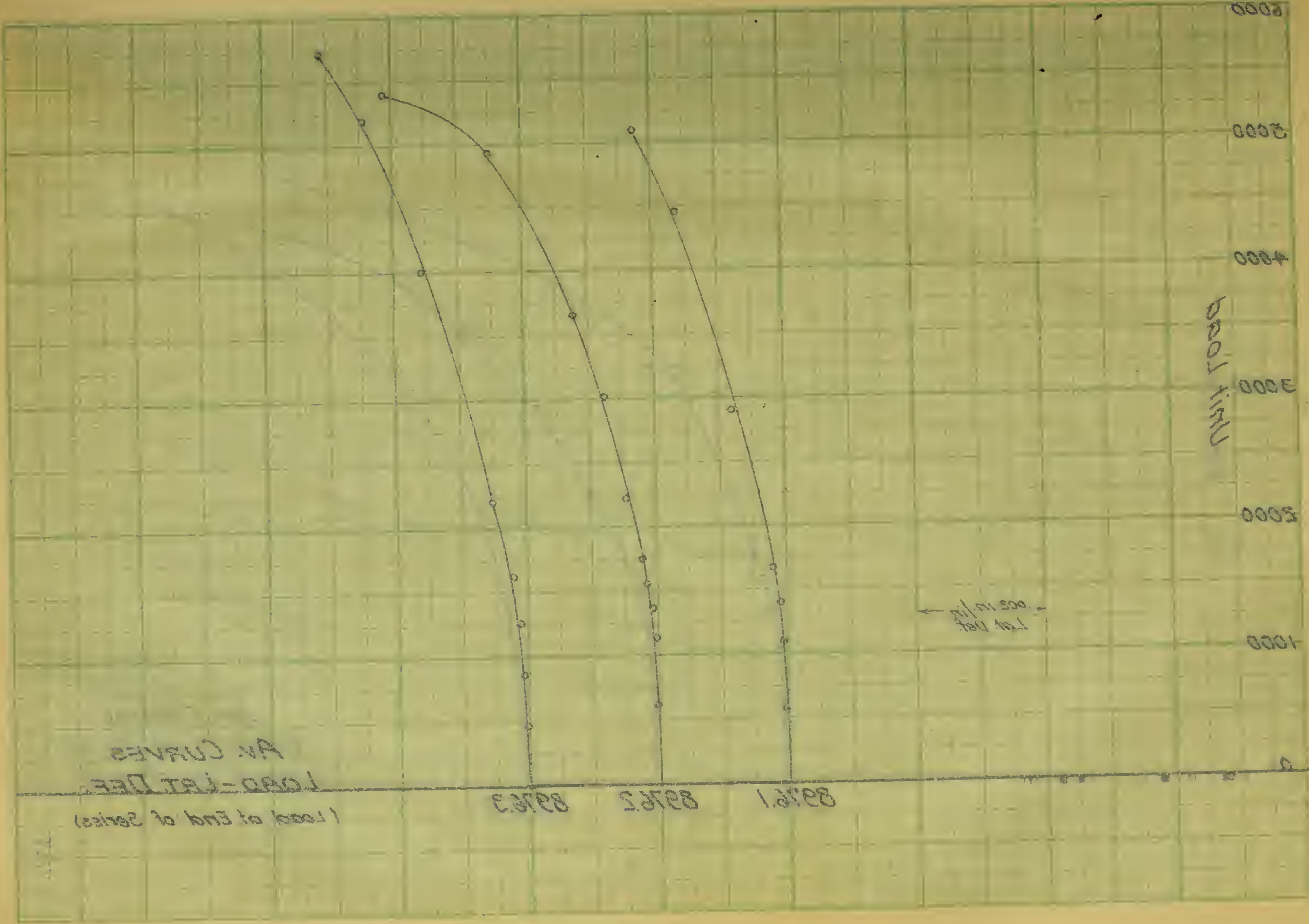

Av. Curves
Load - Lat. Def.
(Load at End of Series)
Unit Load
5000
4000
3000
2000
1000
0
8975.1
8975.2
8975.3
.002 in./in.
Lat. Def



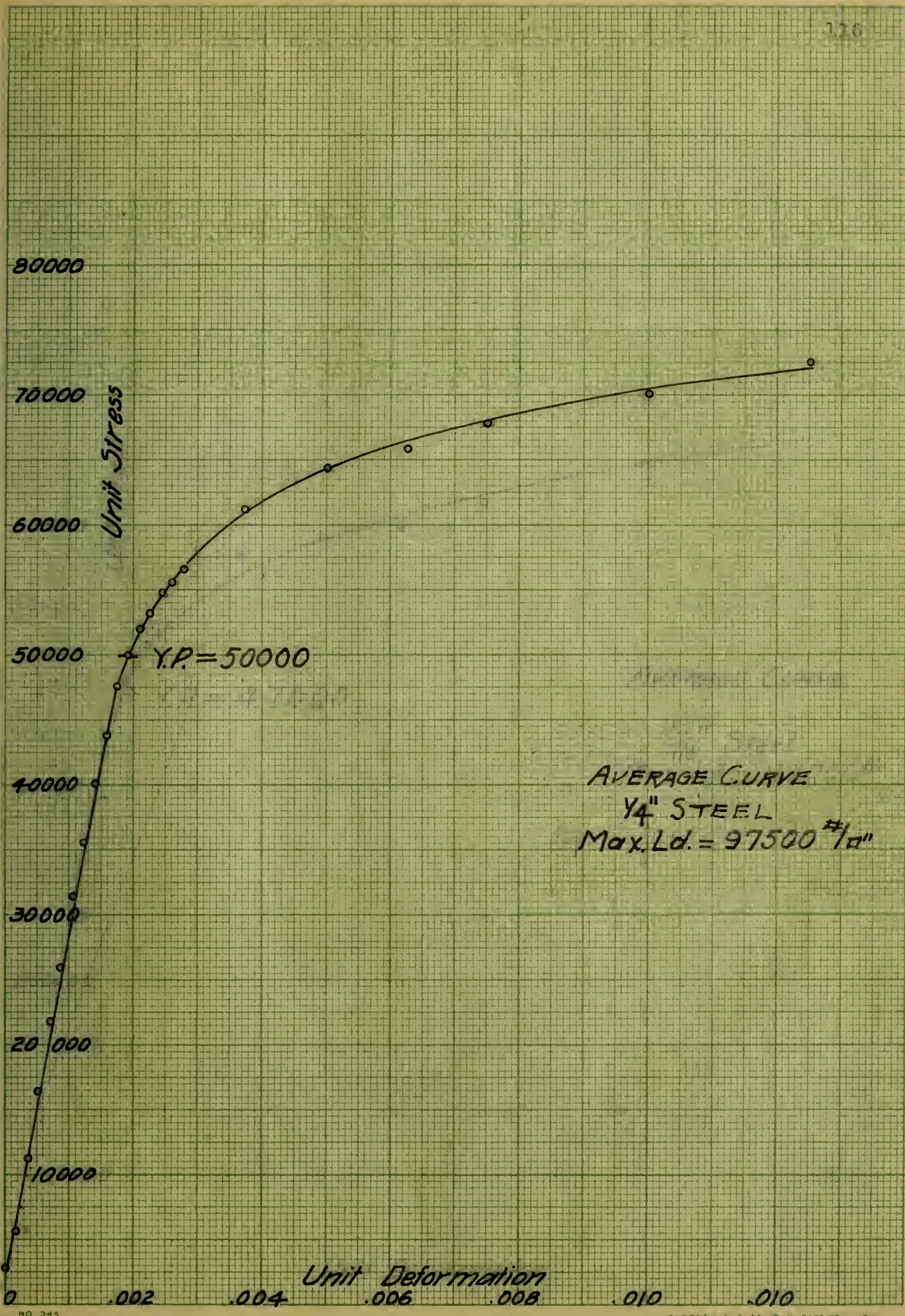
Av. CURVES
LOAD - LAT. DEF.
(Load at End of Series)
8975.1
8975.2
8975.3
Unit Load
0
1000
2000
3000
4000
5000
.002 in./in. Lat. Def.



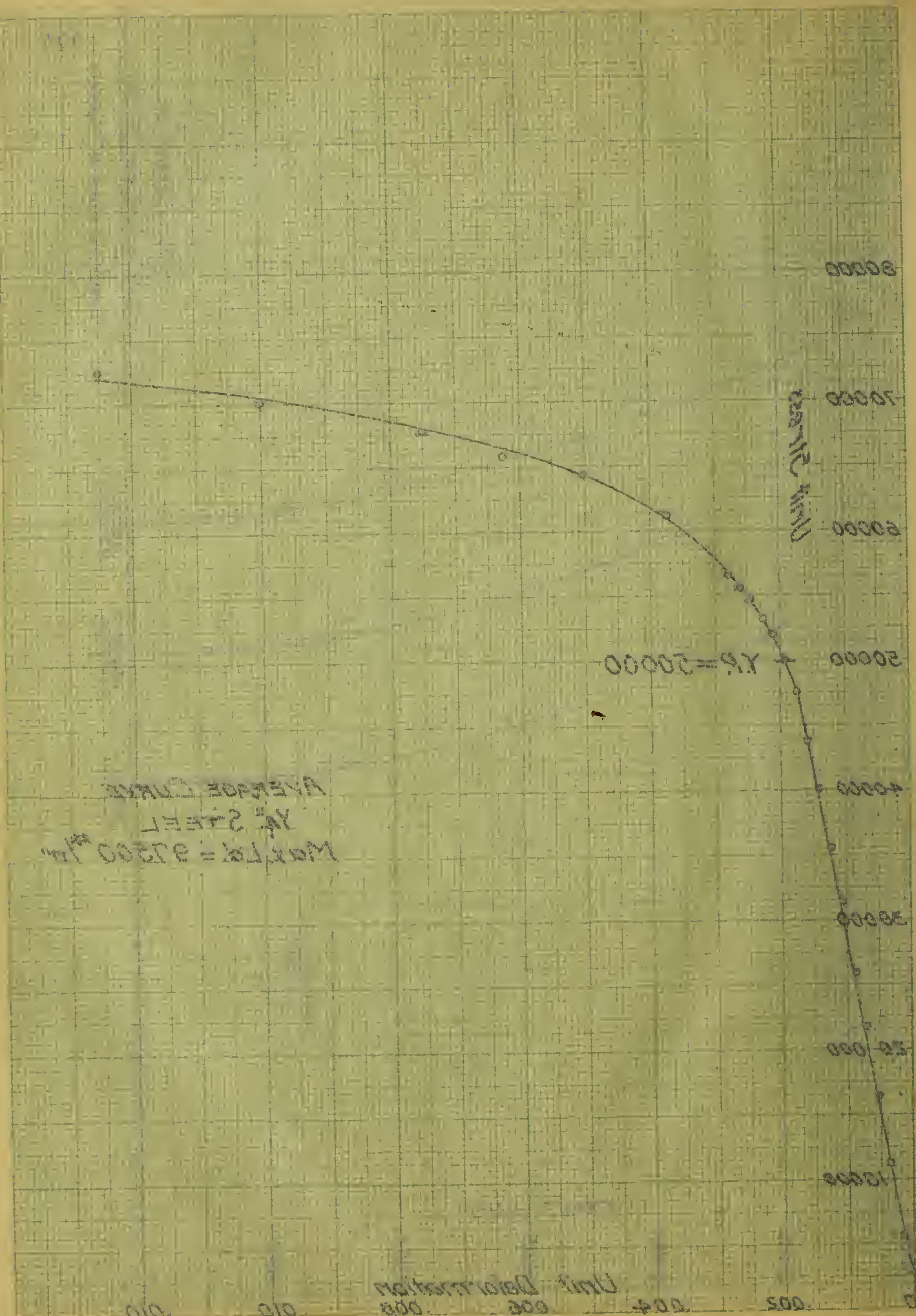
Av. CURVES
LOAD-LAT. DEF.
(Load at End of Series)
Unit Load
6000
5000
4000
3000
2000
1000
0
8976.1
8976.2
8976.3
.002 in./in.
Lat. Def.



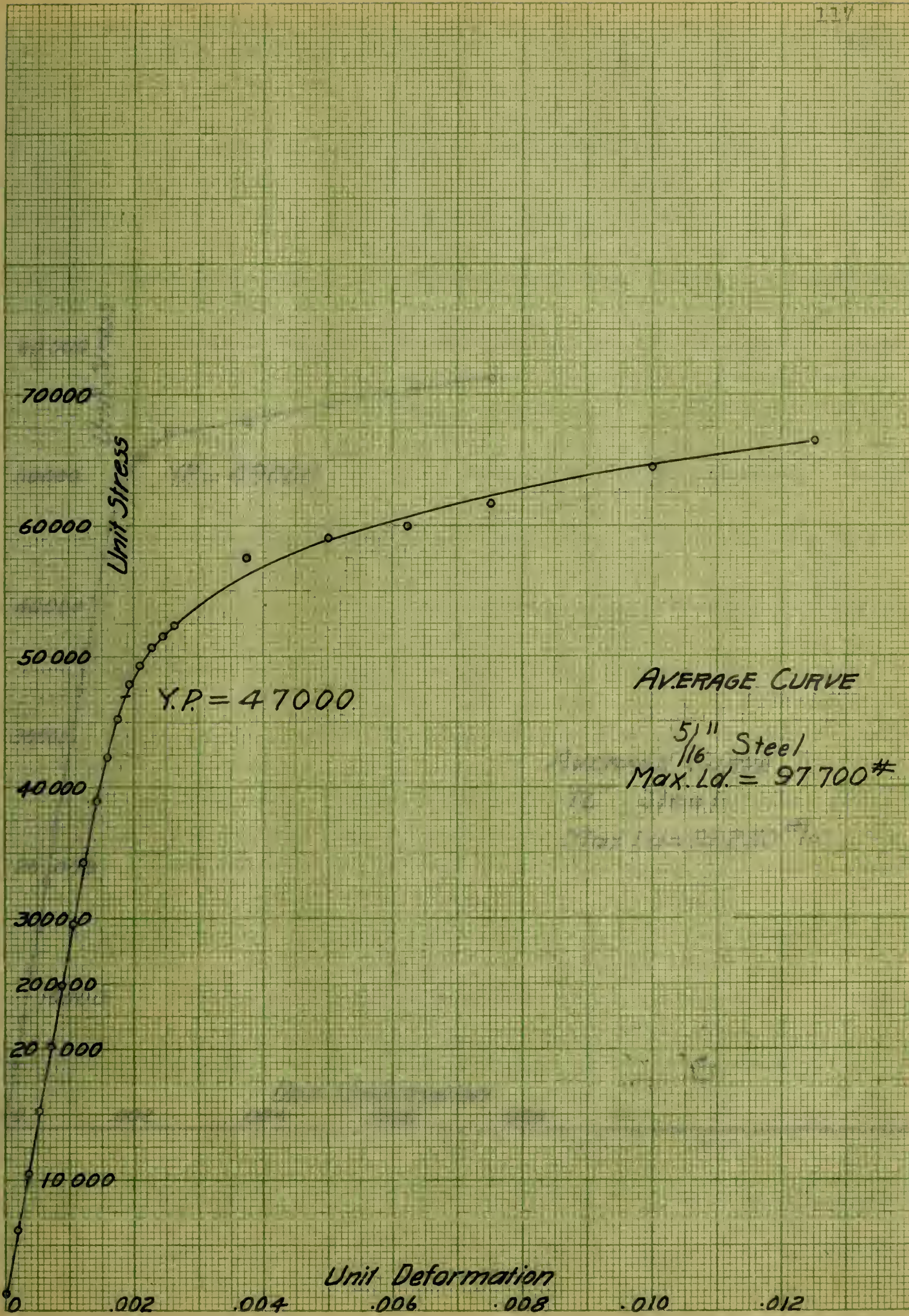
AN CURVES
LOAD-LAT DEF
(Load at End of Series)
8976.3
8976.2
8976.1
Unit Load
.002 in./in. Lat Def
0
1000
2000
3000
4000
5000
6000

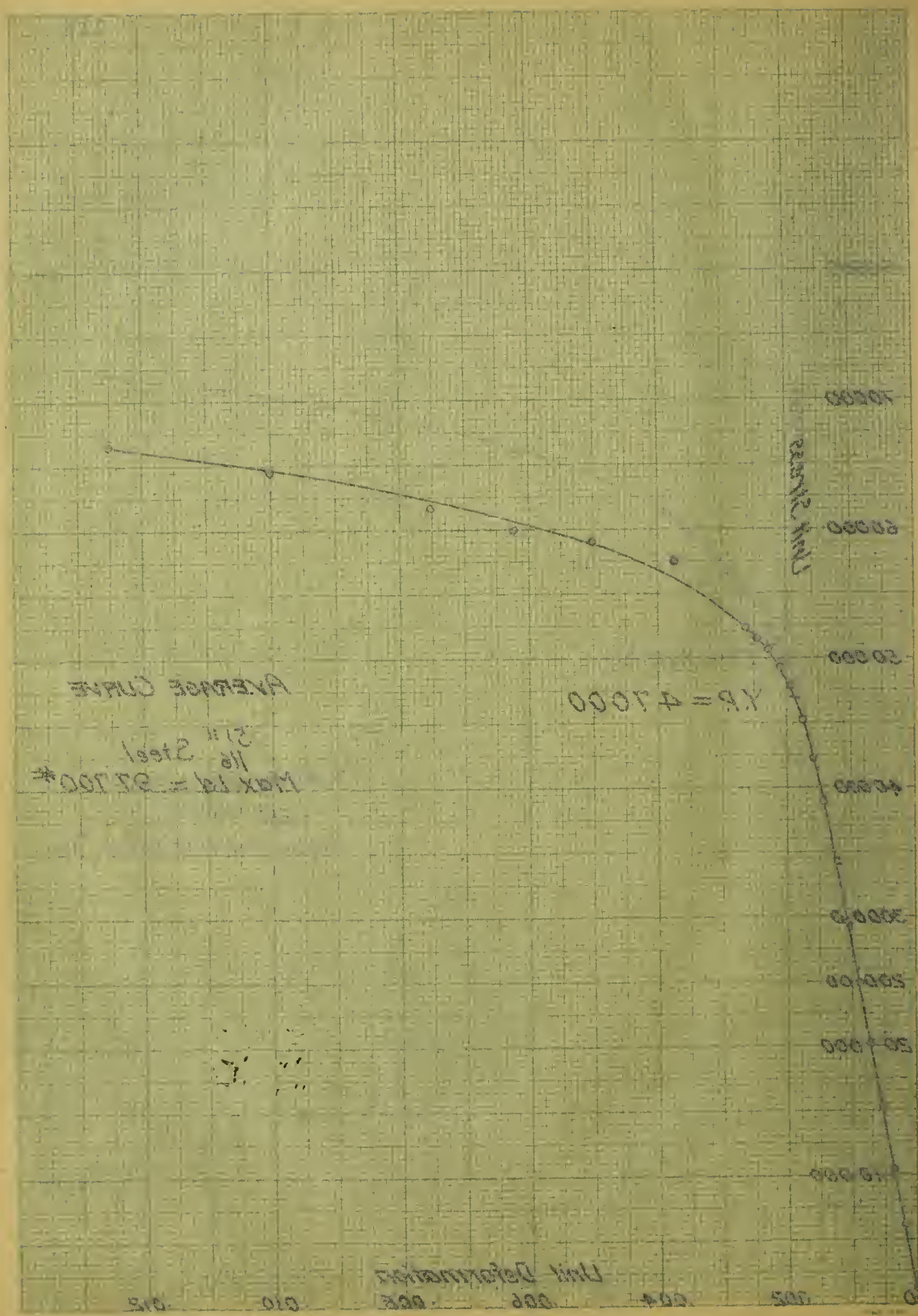

Unit Stress
80000
70000
60000
50000
40000
30000
20000
10000
Y.P.=50000
AVERAGE CURVE
1/4" STEEL
Max. Ld. = 97500 #/□"
Unit Deformation
0
.002
.004
.006
.008
.010
.010

NO 345

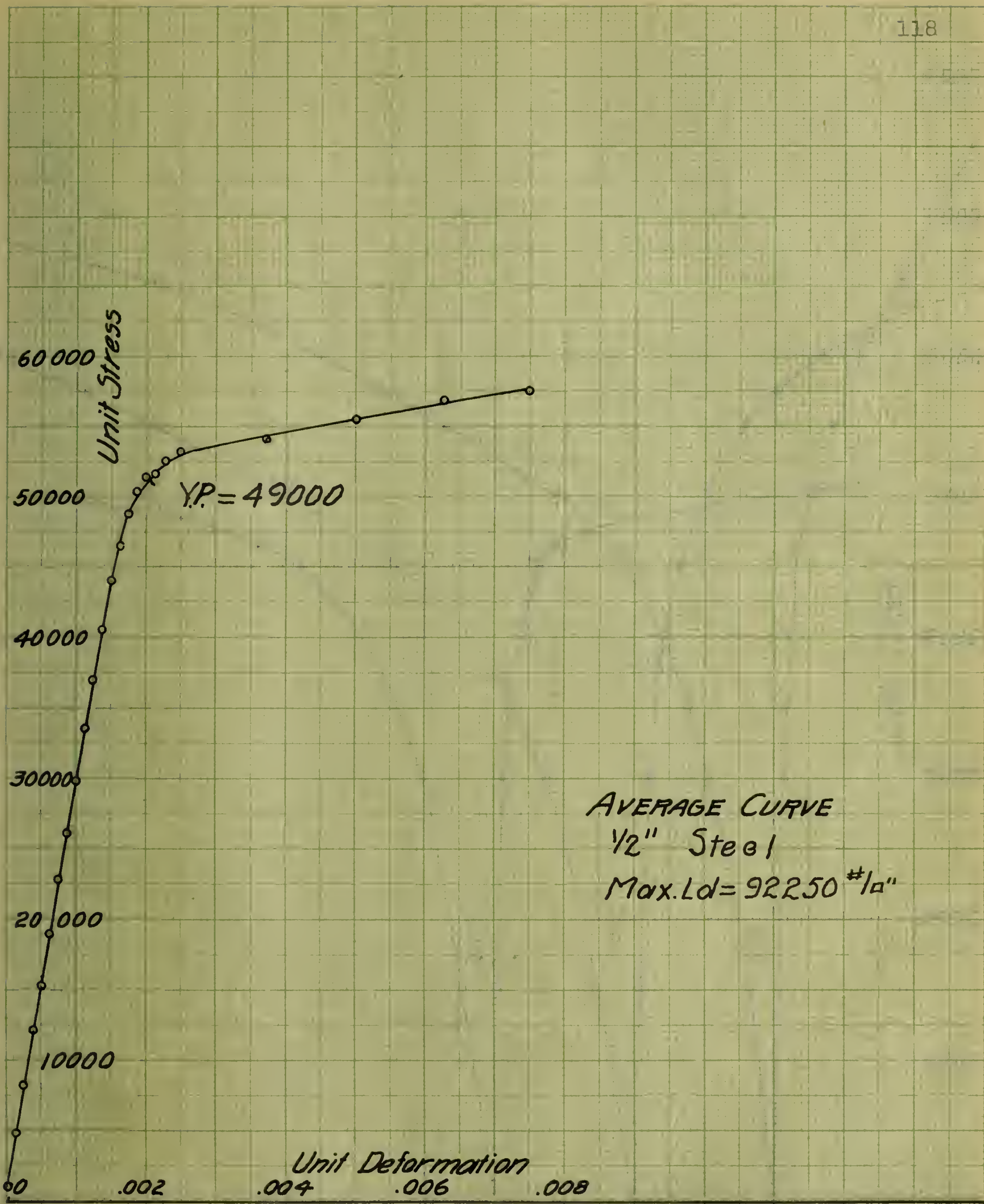


Average Curve
1/2" Steel
Max Ld = 97500 #/in"
Y.P. = 50000
Unit Stress
Unit Deformation
80000
70000
60000
50000
40000
30000
20000
10000
.002
.004
.006
.008

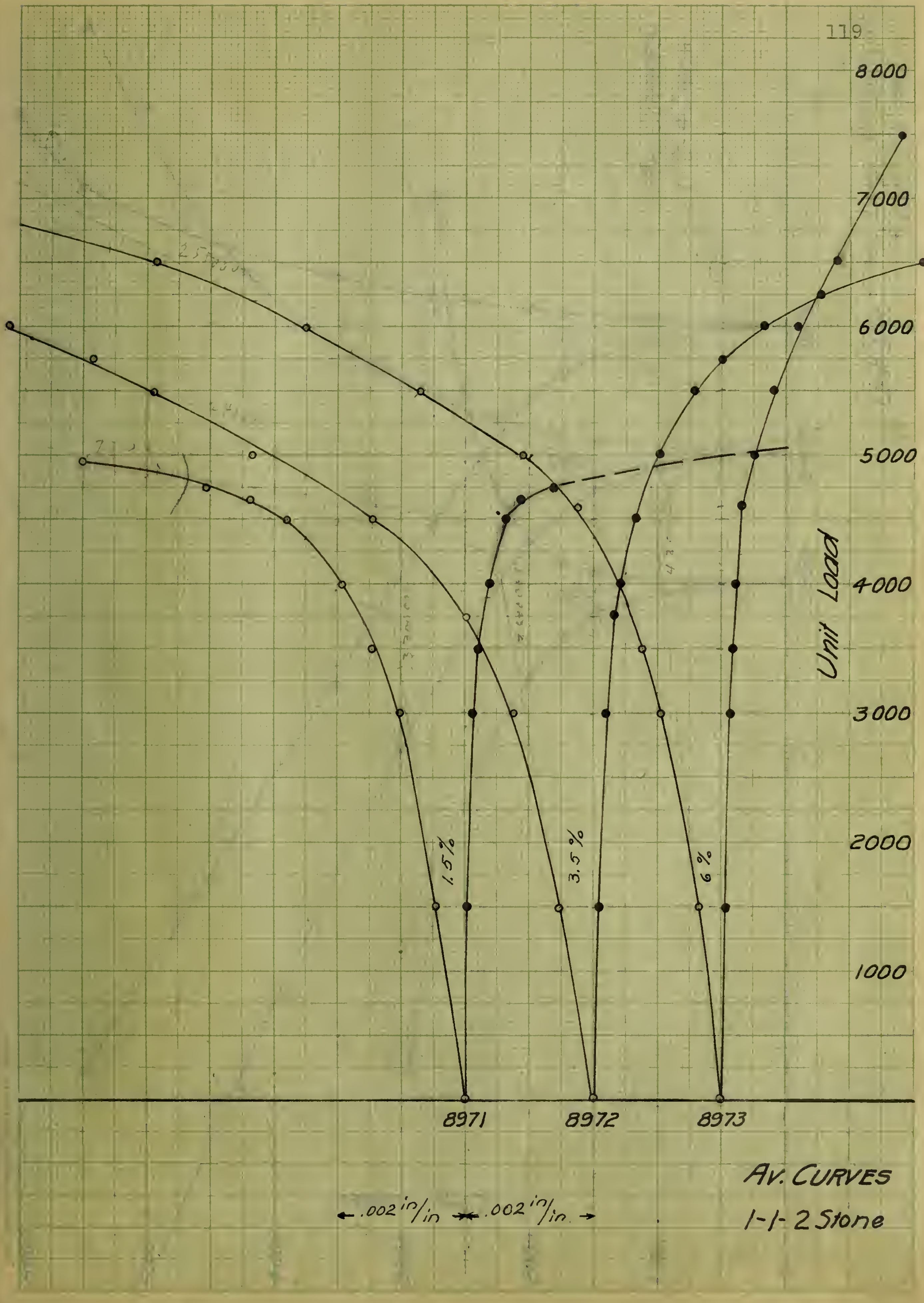

70000
60000
50000
40000
30000
20000
20000
10000
0
.002
.004
.006
.008
.010
.012
Unit Stress
Unit Deformation
Y.P. = 47000
AVERAGE CURVE
5/16" Steel
Max. Ld. = 97700#

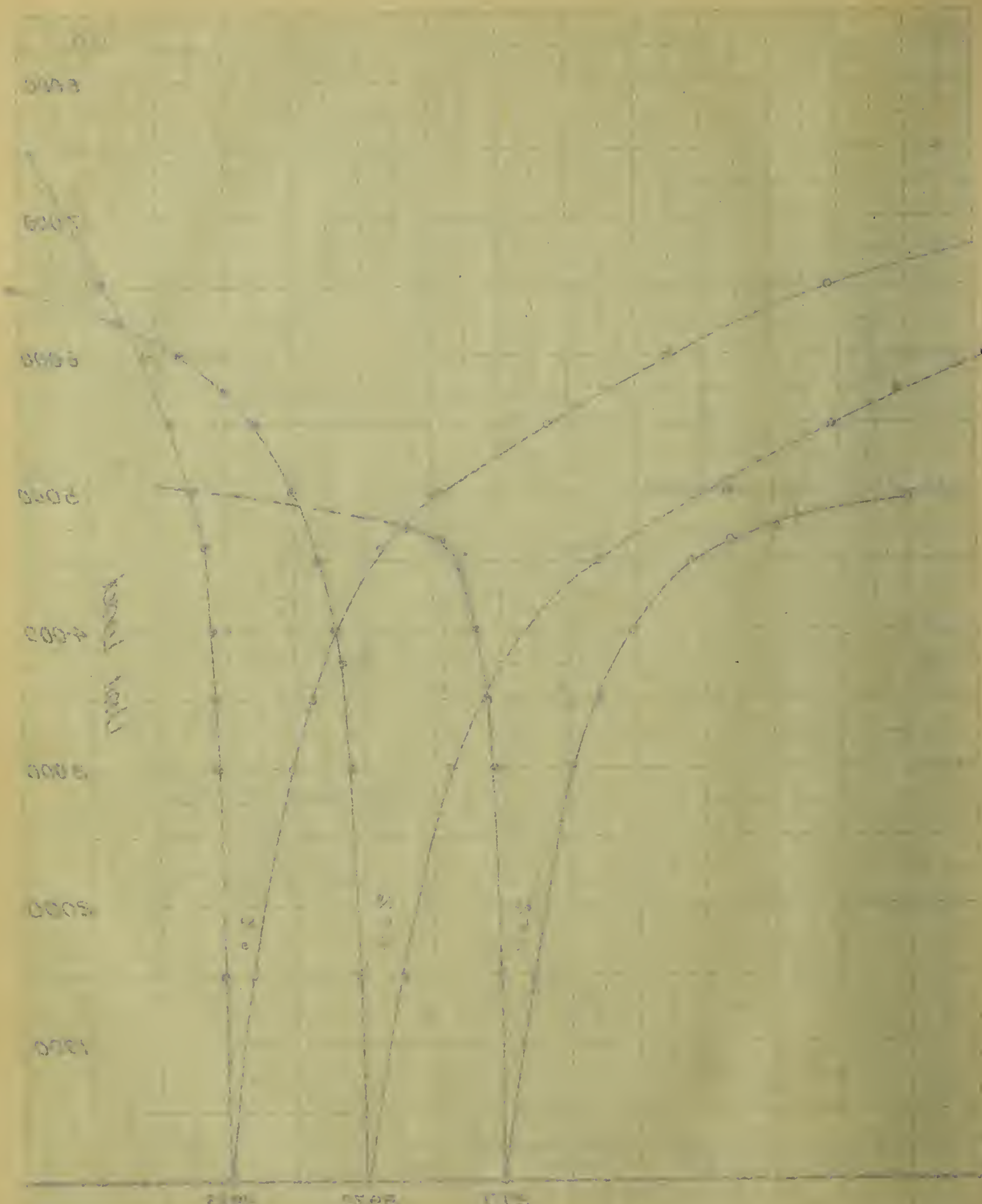


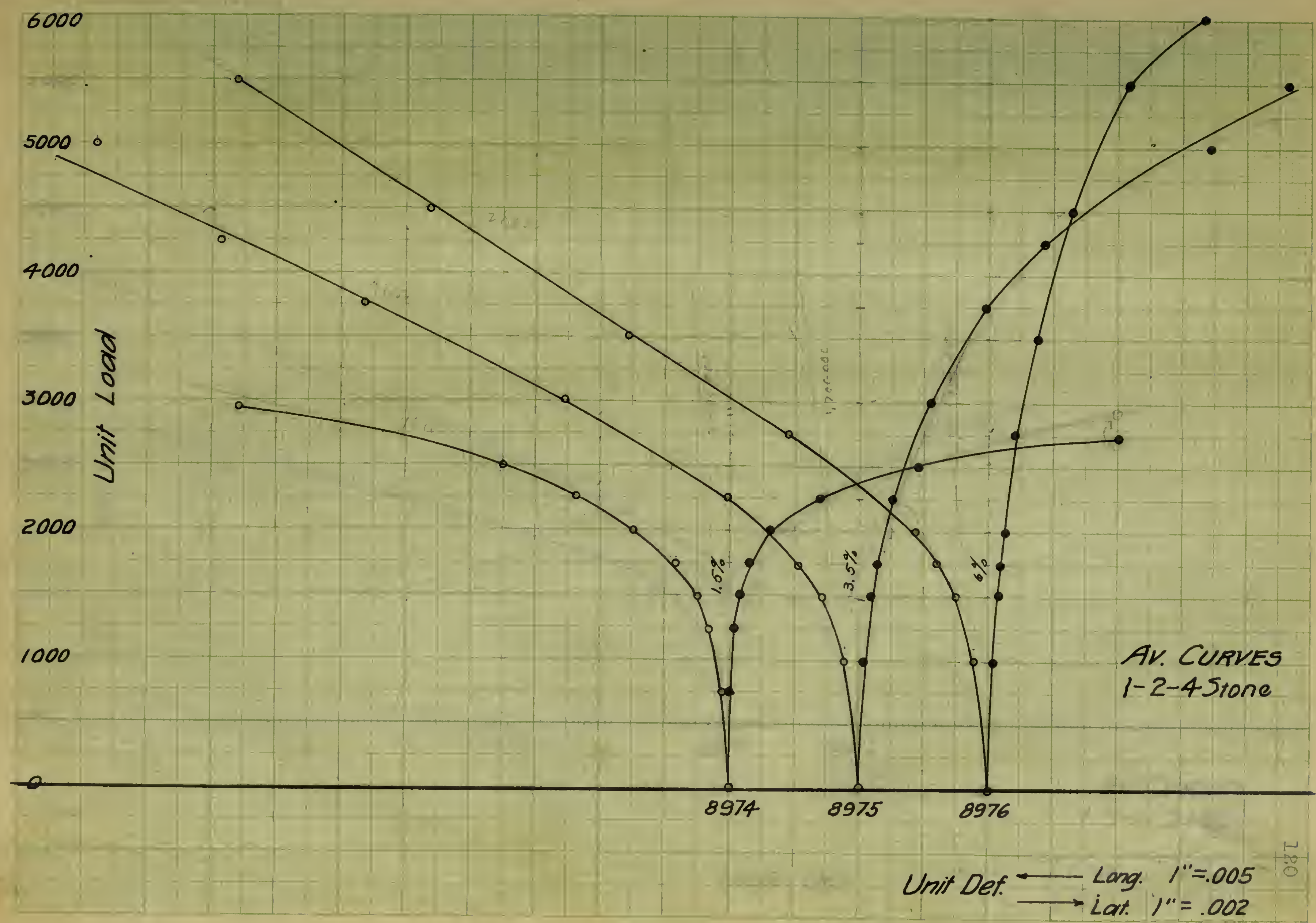
Average Curve
5/16" Steel
Y.P. = 47000
Unit Stress
Unit Deformation

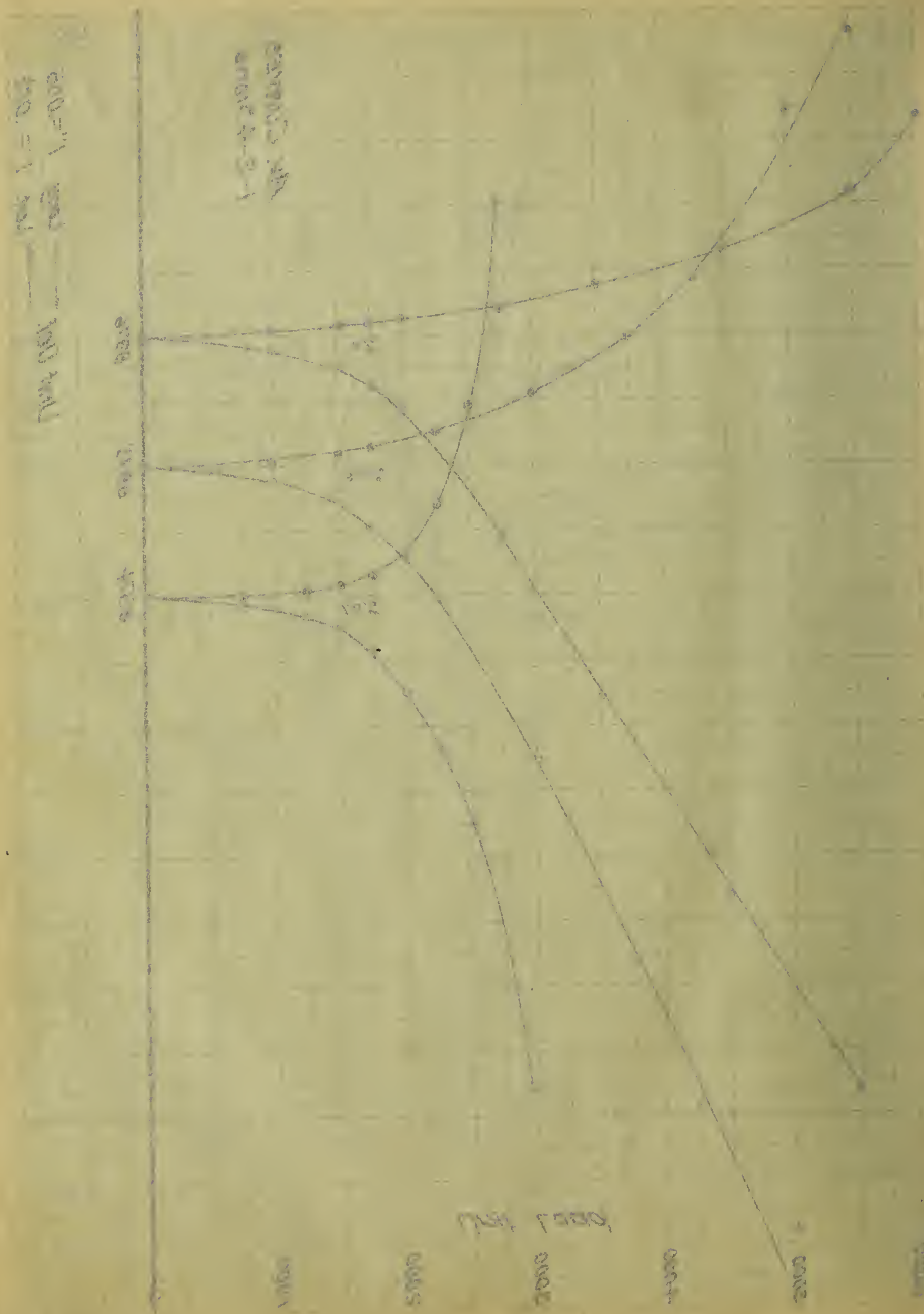


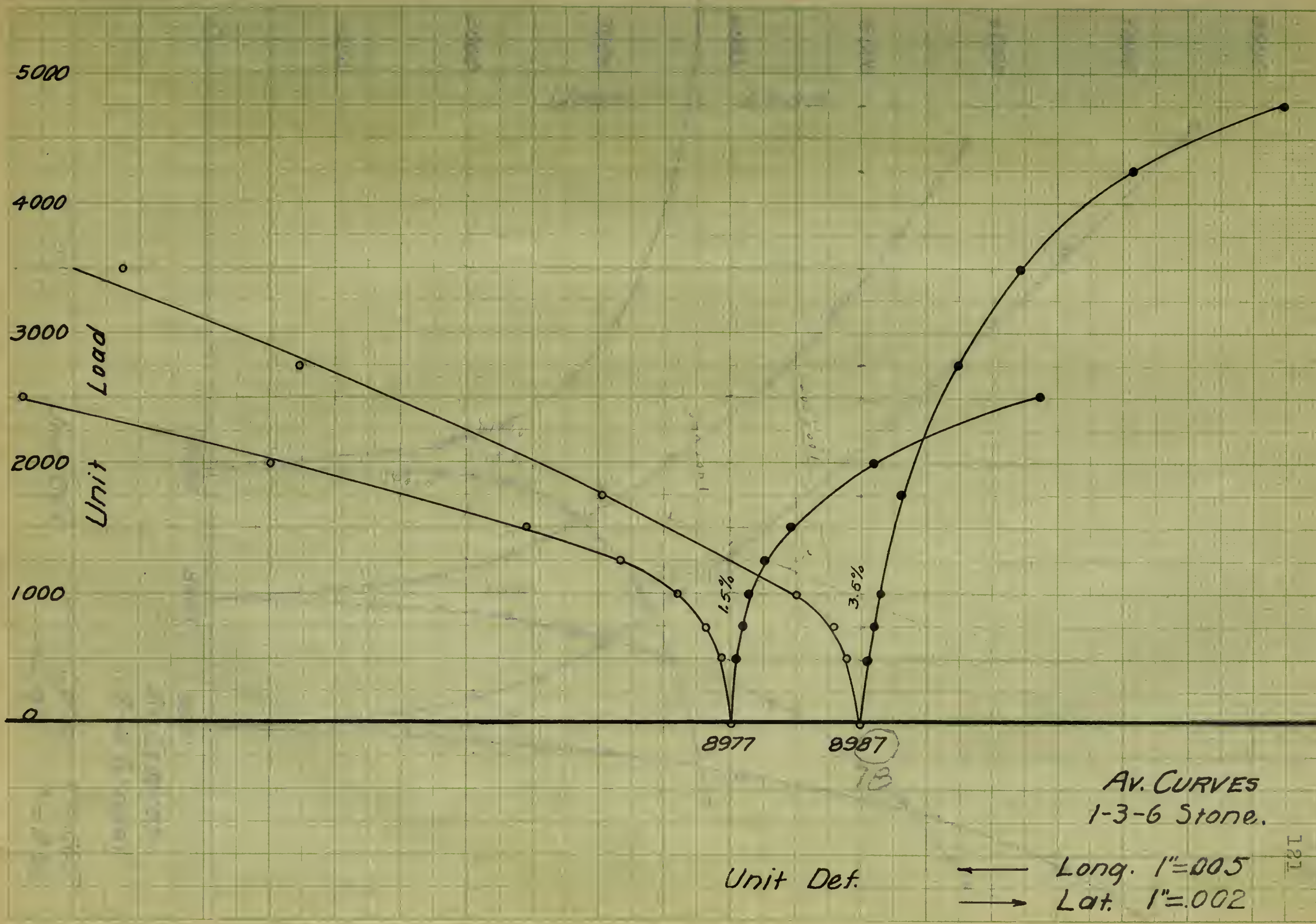
Unit Stress
60000
50000
40000
30000
20000
10000
Y.P. = 49000
Unit Deformation
0
.002
.004
.006
.008
Average Curve
1/2" Steel
Max. Ld = 92250 #/□"


8000
7000
6000
5000
4000
3000
2000
1000
Unit Load
1.5%
3.5%
6%
8971
8972
8973
← .002 in/in → ← .002 in/in. →
Av. Curves
1-1-2 Stone

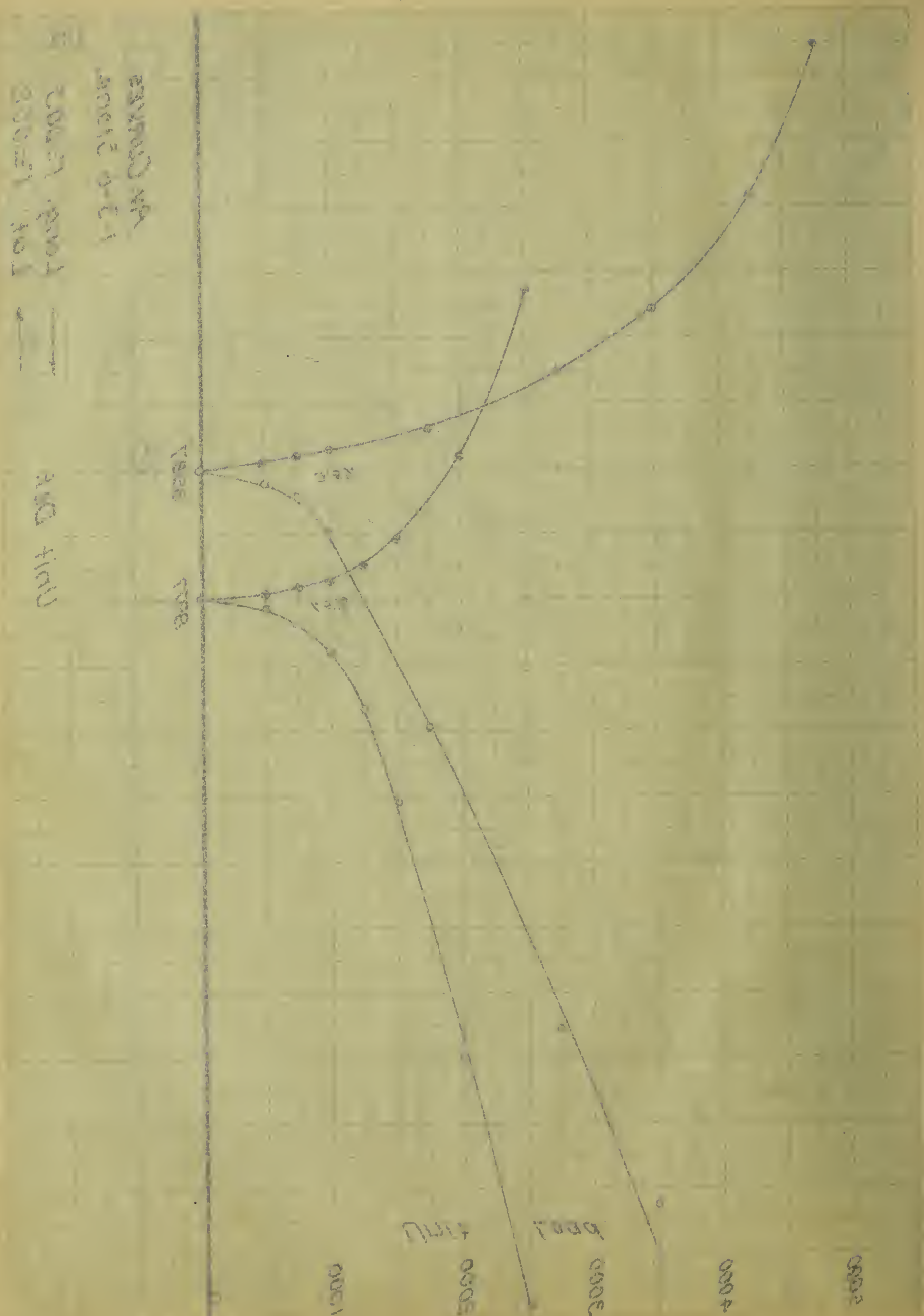


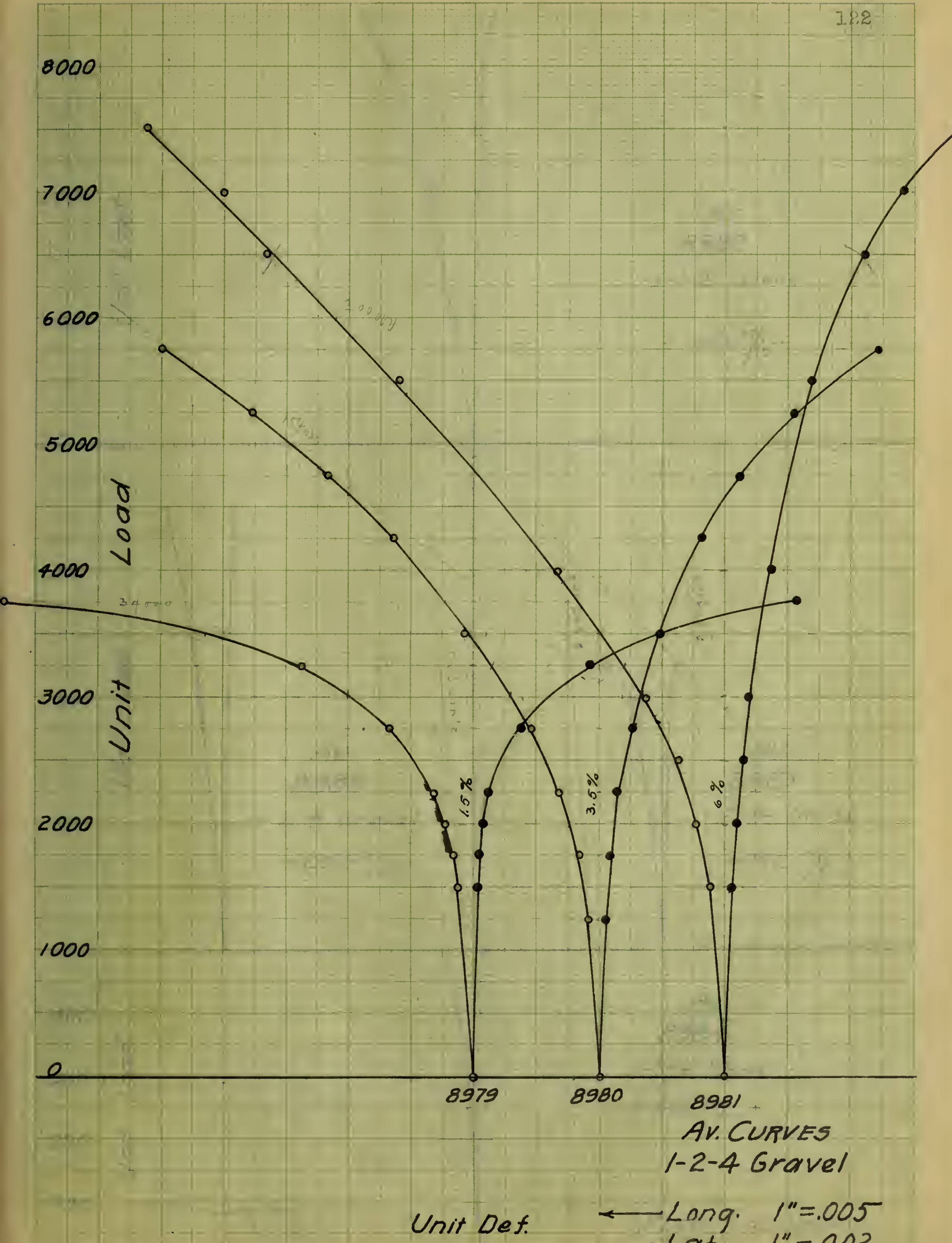

Av. Curves
1-2-4 Stone
Unit Load
6000
5000
4000
3000
2000
1000
0
8974
8975
8976
1.5%
3.5%
6%
Unit Def.
Long. 1" = .005
Lat. 1" = .002
120



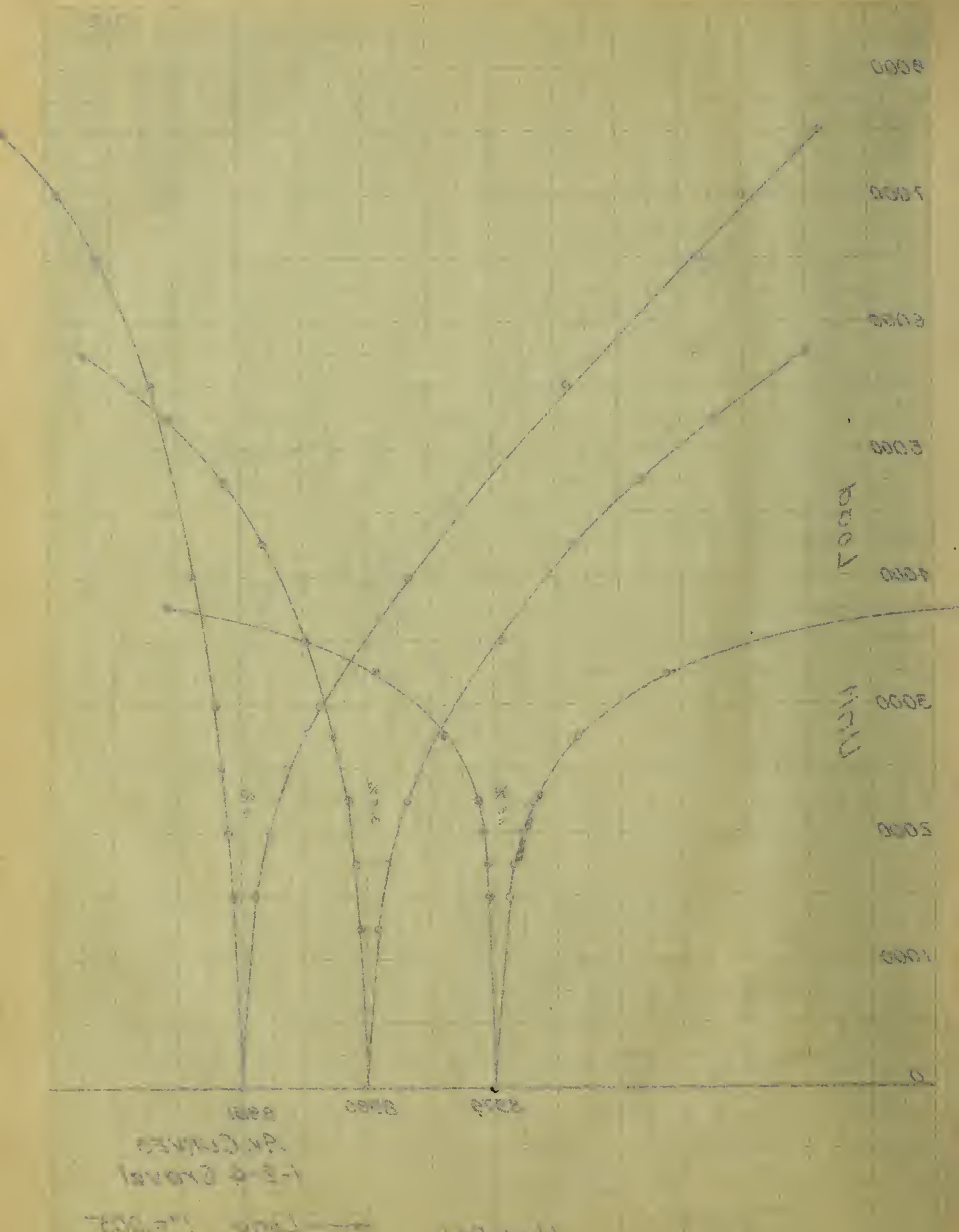


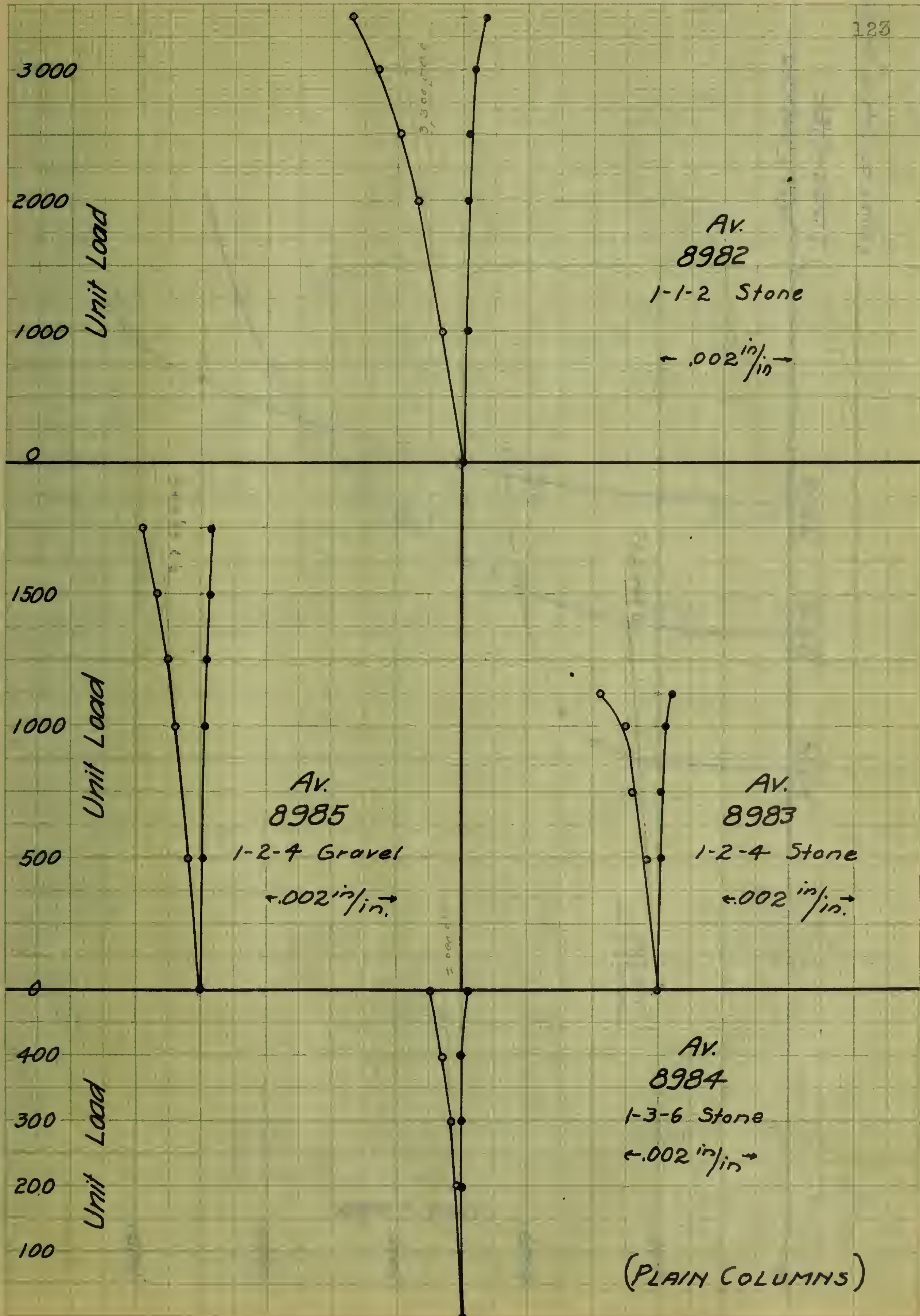
5000
4000
3000
2000
1000
0
Unit Load
1.5%
3.6%
8977
8987
1B
Av. CURVES
1-3-6 Stone.
Unit Def.
Long. 1"=.005
Lat. 1"=.002
121

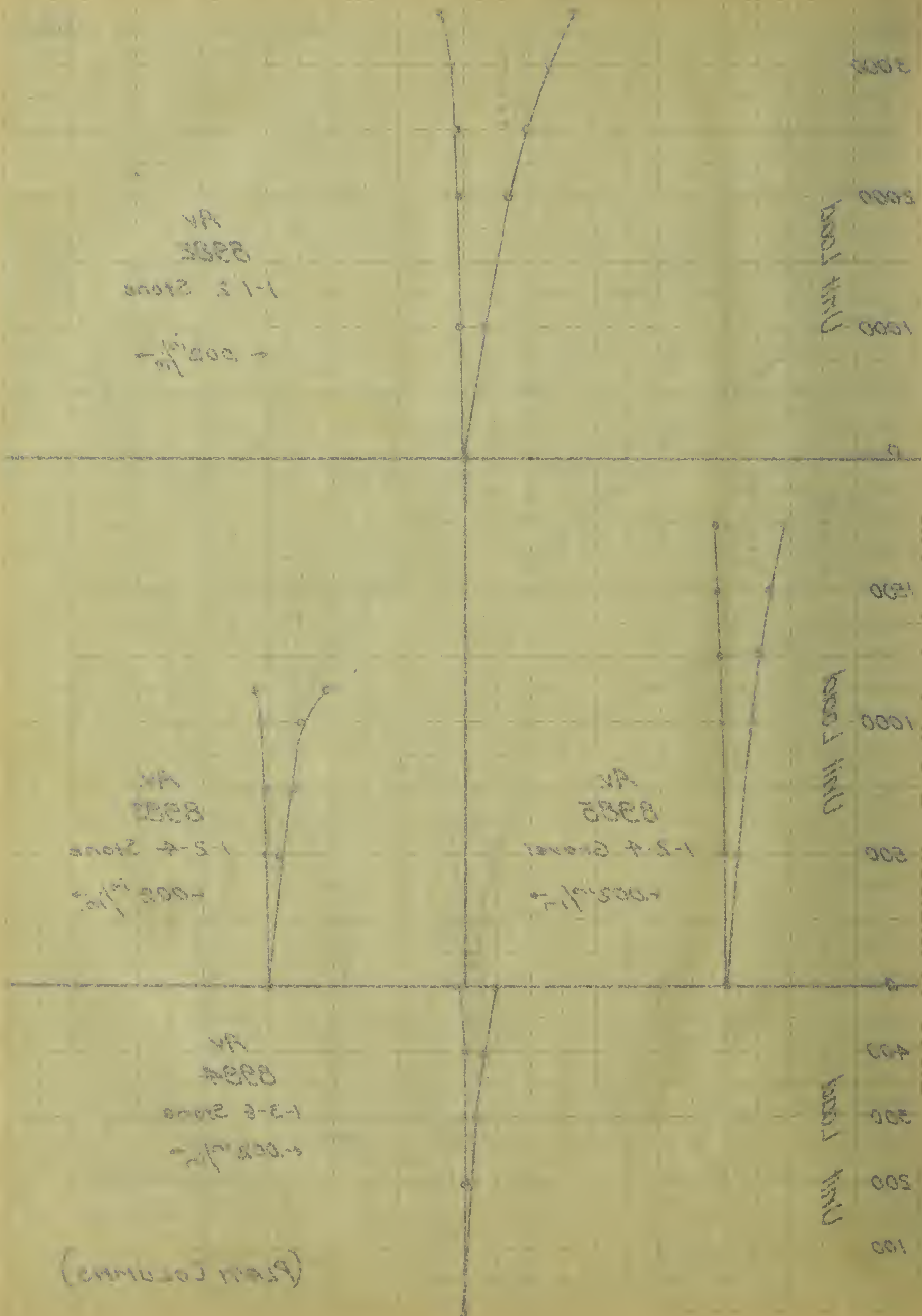




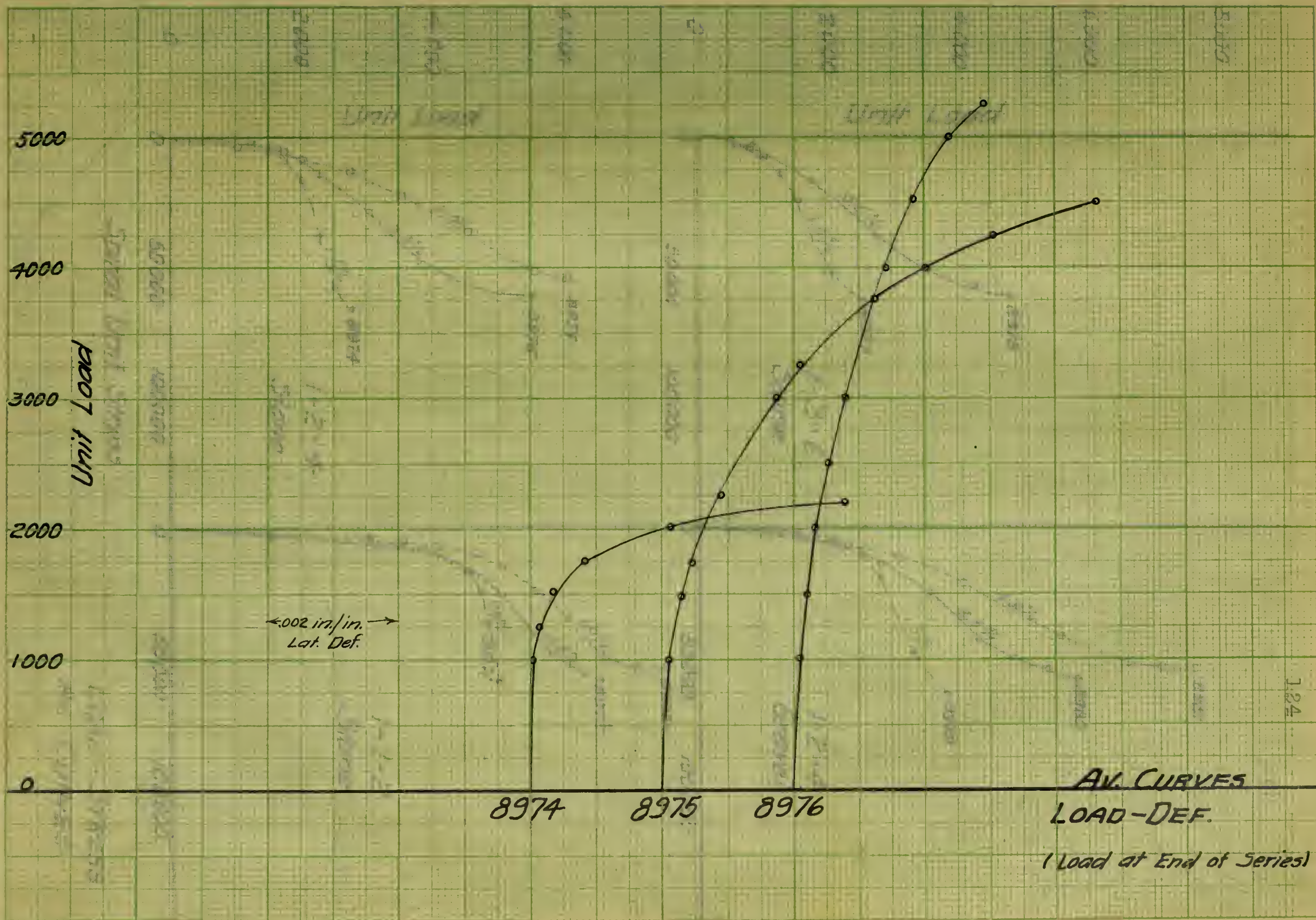
Av. CURVES
1-2-4 Gravel


8000
7000
6000
5000
4000
3000
2000
1000
0

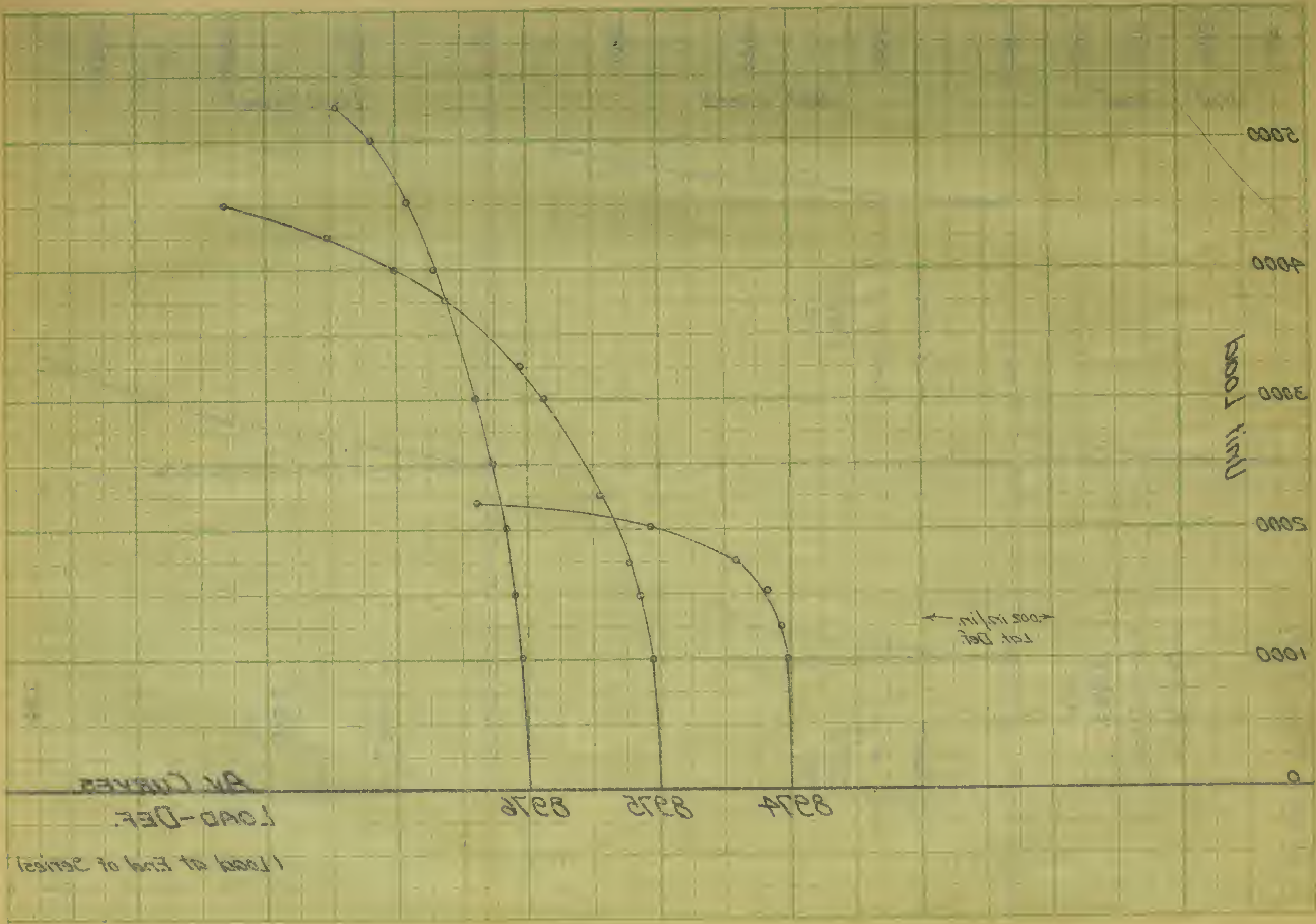

3000
2000
1000
0
Unit Load
Av.
8982
1-1-2 Stone
←.002 in/in→
1500
1000
500
0
Unit Load
Av.
8985
1-2-4 Gravel
←.002 in/in→
Av.
8983
1-2-4 Stone
←.002 in/in→
400
300
200
100
Unit Load
Av.
8984
1-3-6 Stone
←.002 in/in→
(PLAIN COLUMNS)



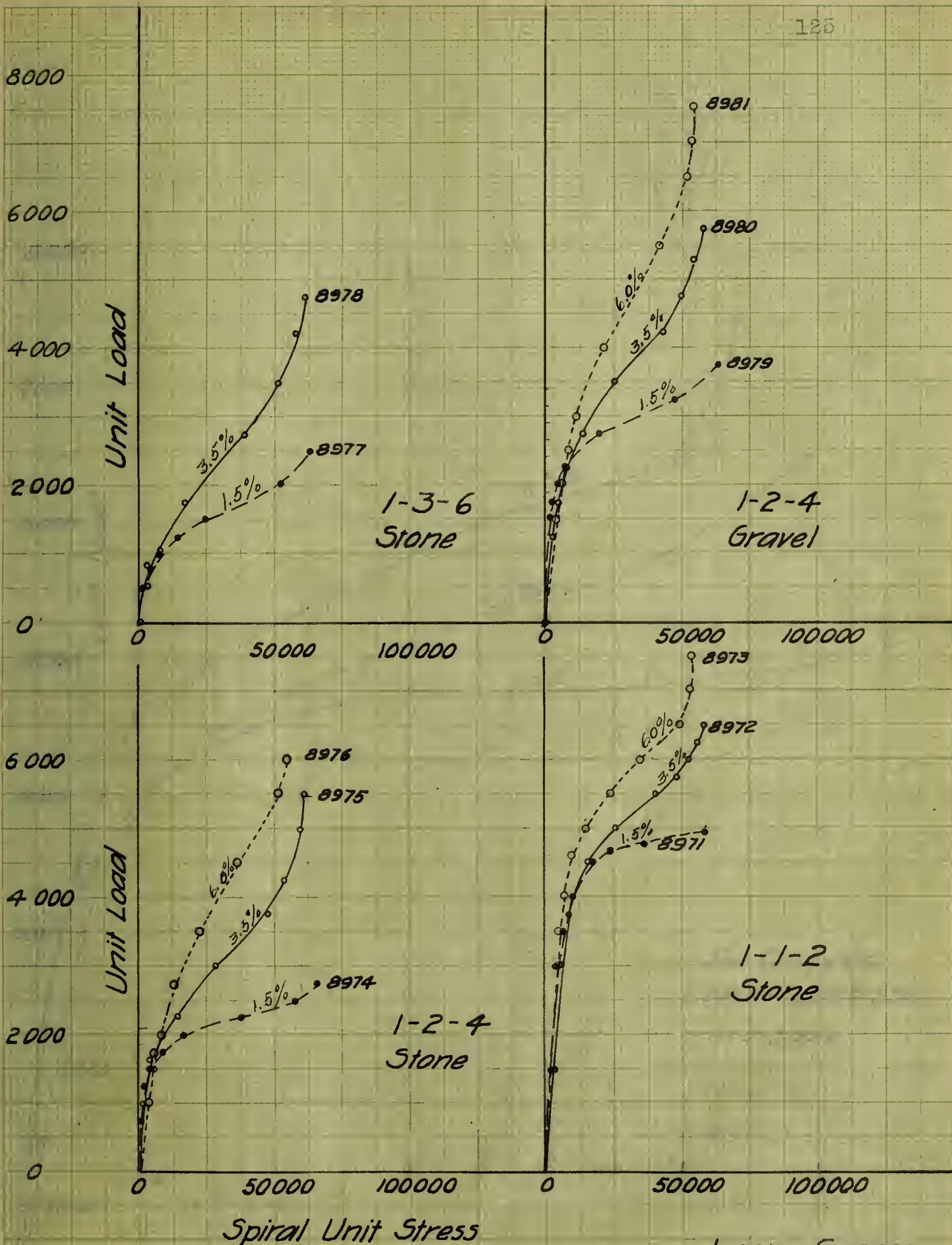
Unit Load
Unit Load
Unit Load
(Plain Columns)



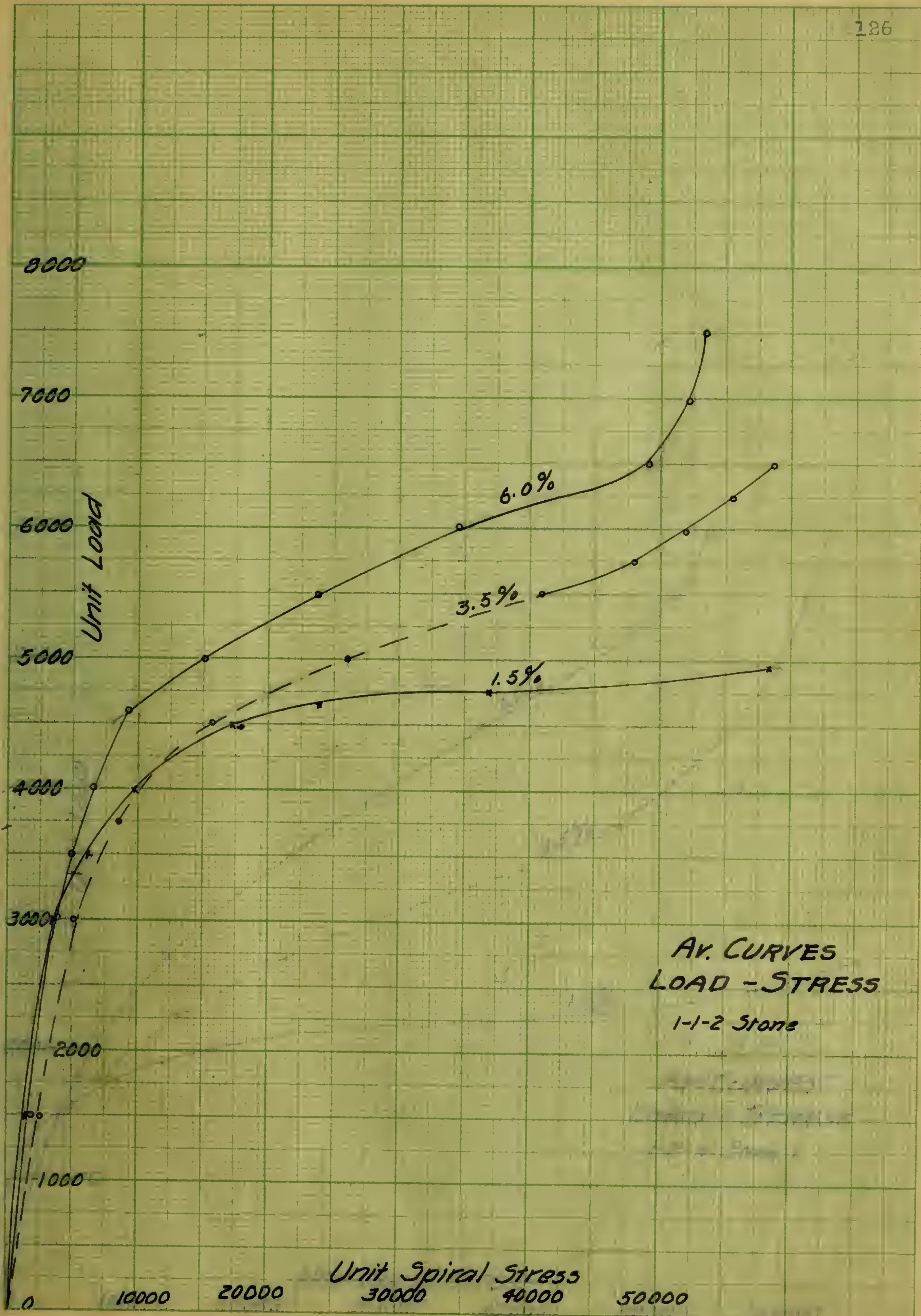
Unit Load
5000
4000
3000
2000
1000
0
←.002 in./in.→
Lat. Def.
8974
8975
8976
AV. CURVES
LOAD-DEF.
(Load at End of Series)

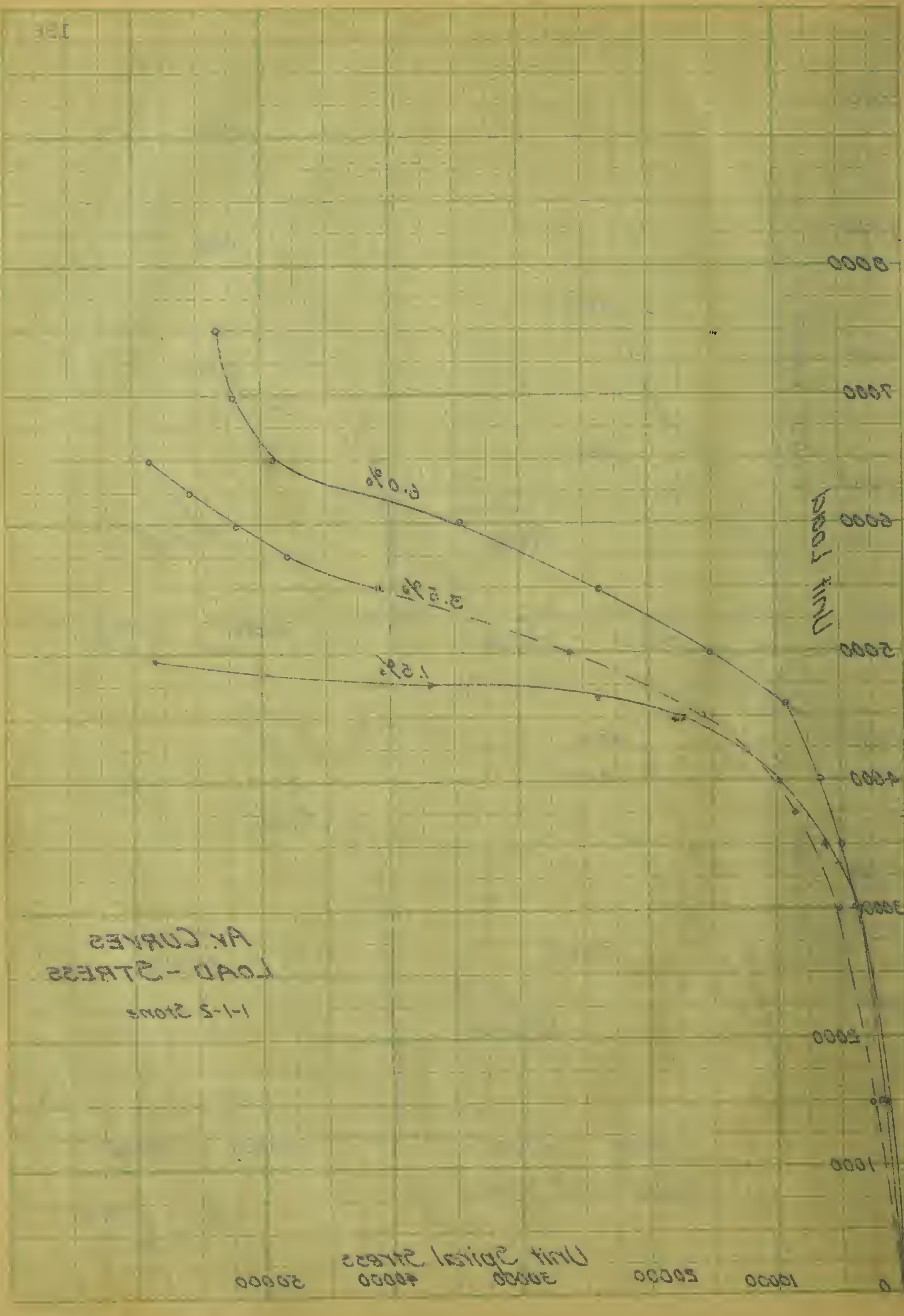


Al Curves
Load-Def.
(Load at End of Series)
8976
8975
8974
.002 in/in
Lat. Def.
Unit Load
0
1000
2000
3000
4000
5000

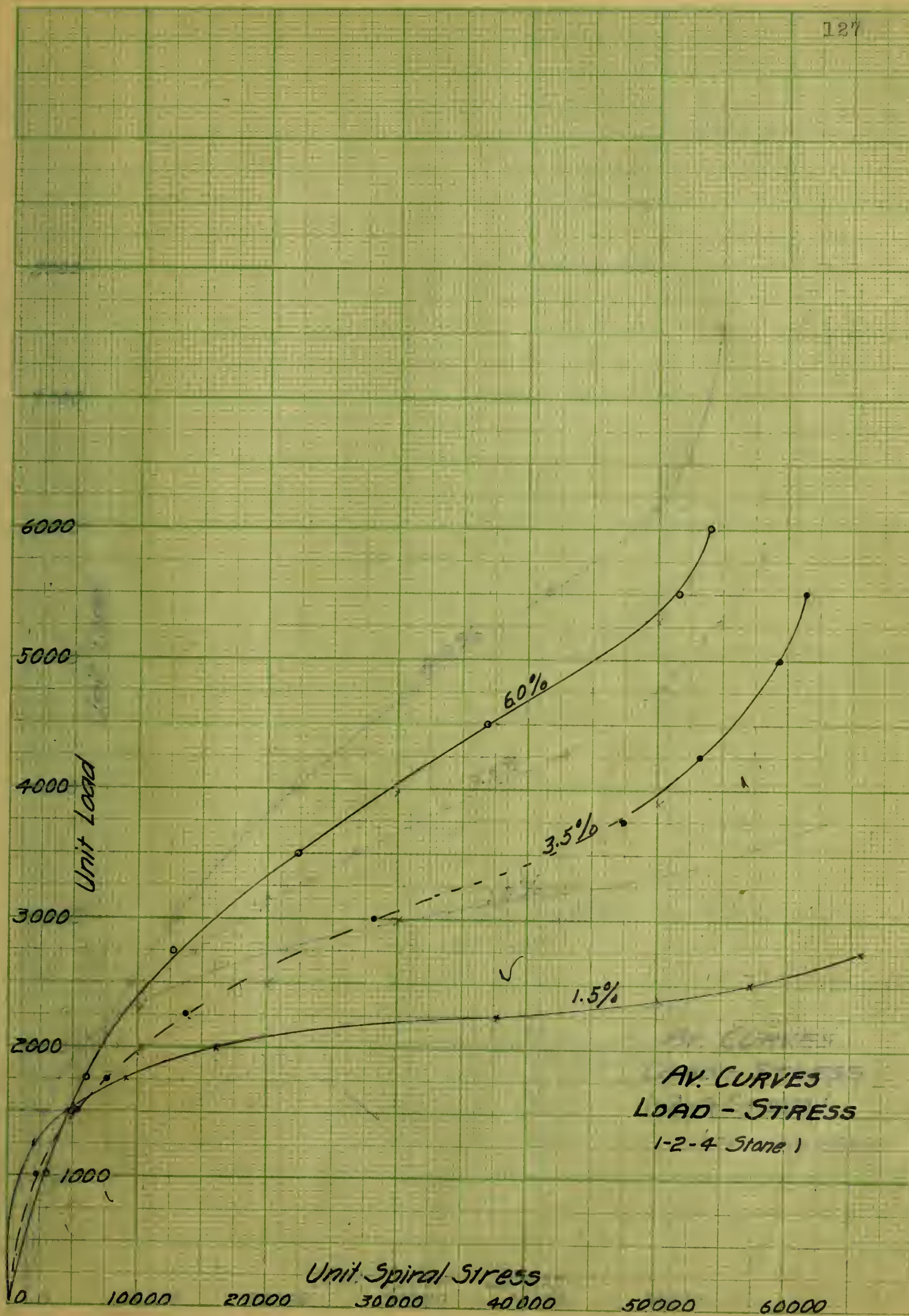


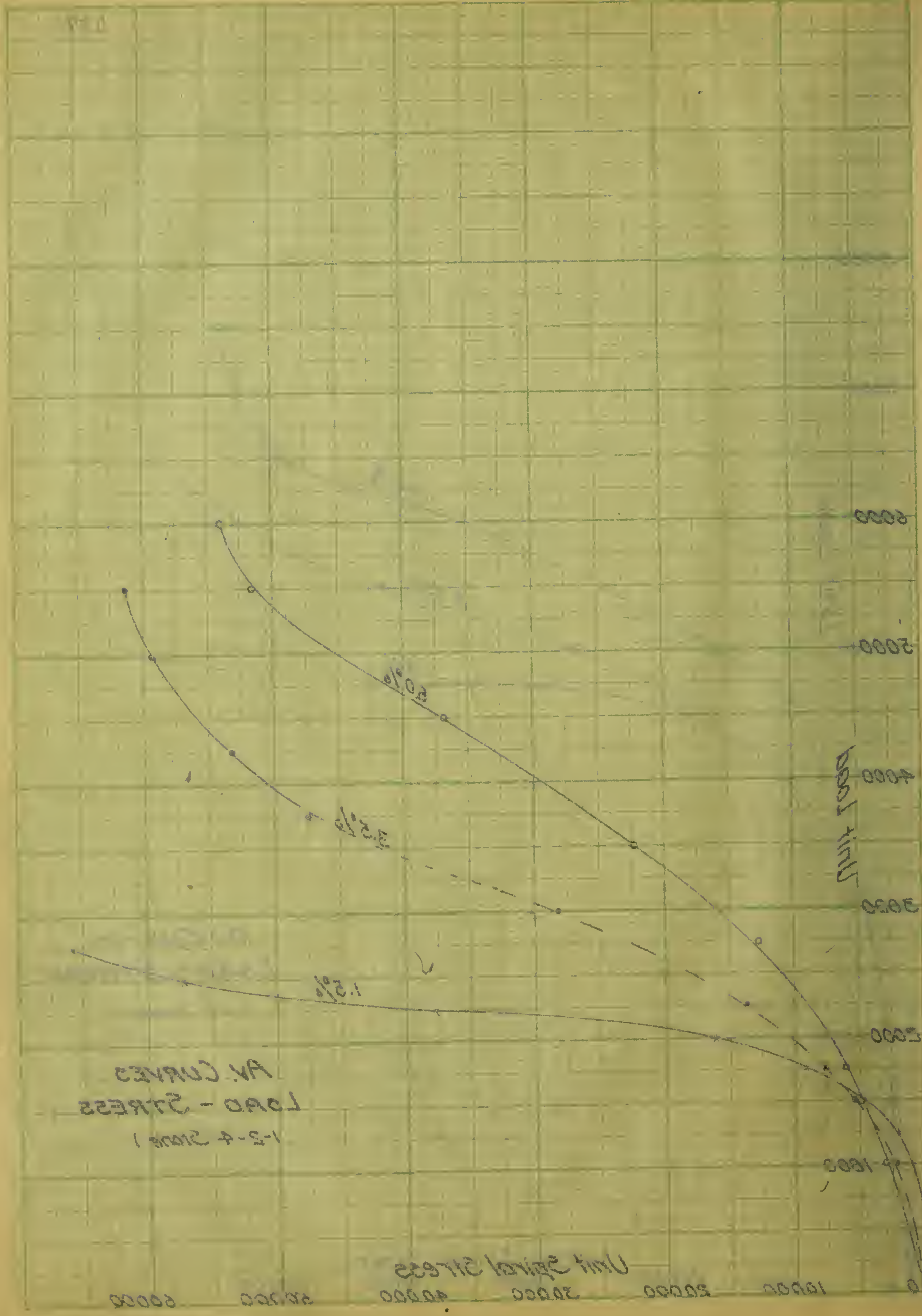
LOAD - STRESS
AV. CURVES


8000
7000
6000
5000
4000
3000
2000
1000
0
10000
20000
30000
40000
50000
Unit Load
Unit Spiral Stress
6.0%
3.5%
1.5%
Av. CURVES
LOAD - STRESS
1-1-2 Stone

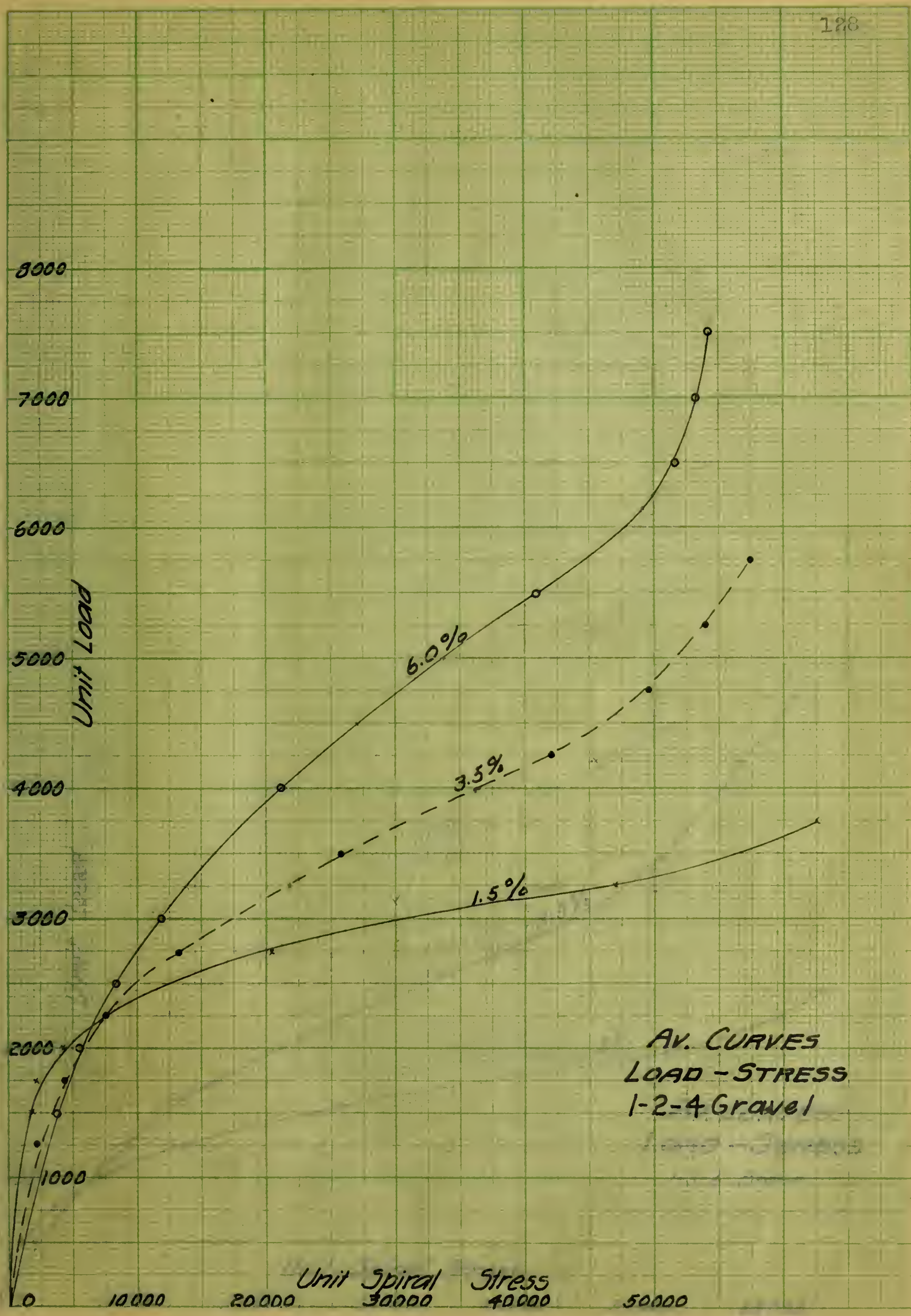


Ak CURVES
LOAD - STRESS
1-1-2 Stone
6.0%
3.5%
1.5%
Unit Load
Unit Spiral Stress
0
10000
20000
30000
40000
50000
1000
2000
3000
4000
5000
6000
7000
8000

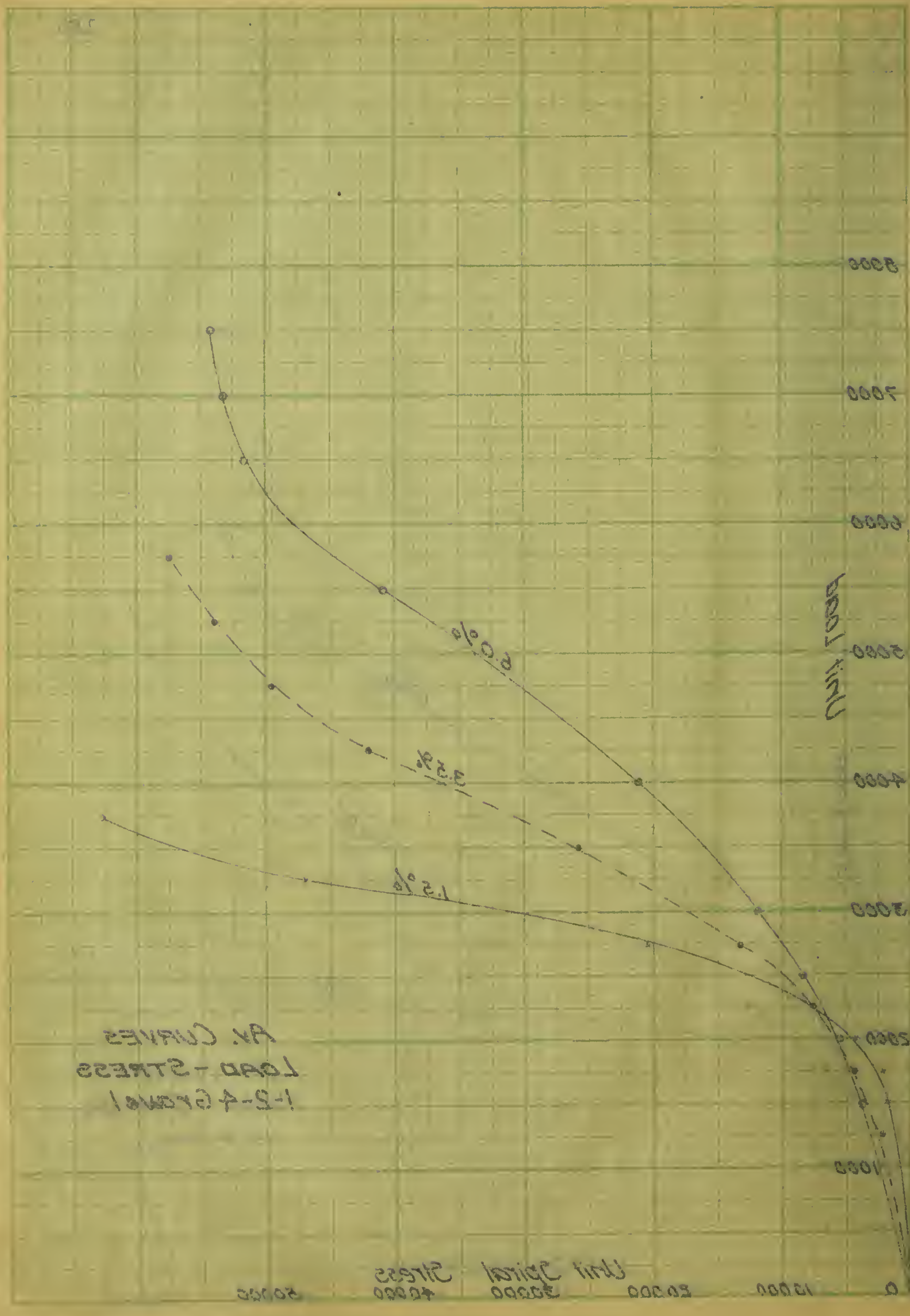

6000
5000
4000
3000
2000
1000
0
10000
20000
30000
40000
50000
60000
Unit Load
Unit Spiral Stress
6.0%
3.5%
1.5%
Av. Curves
Load - Stress
1-2-4 Stone)

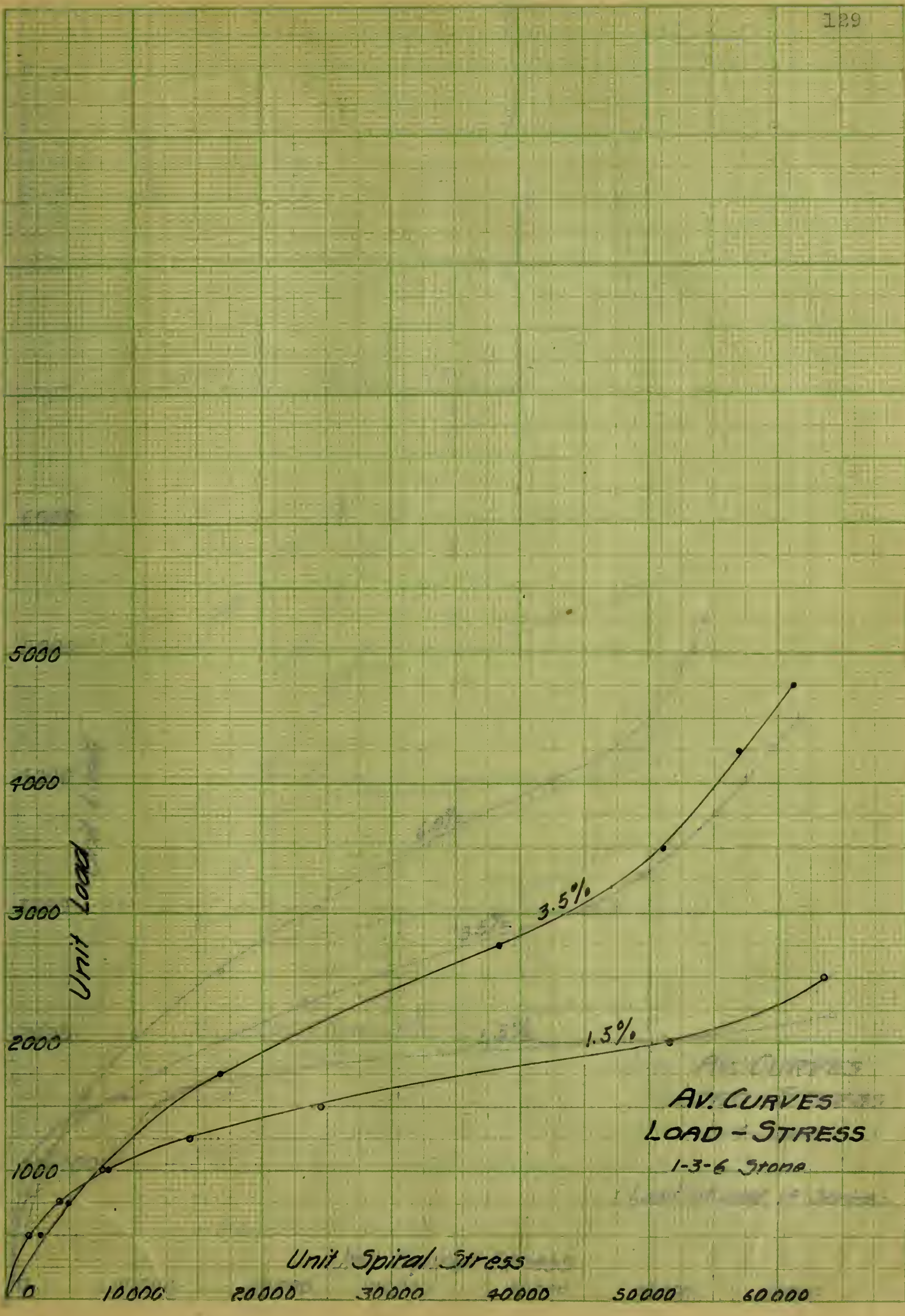


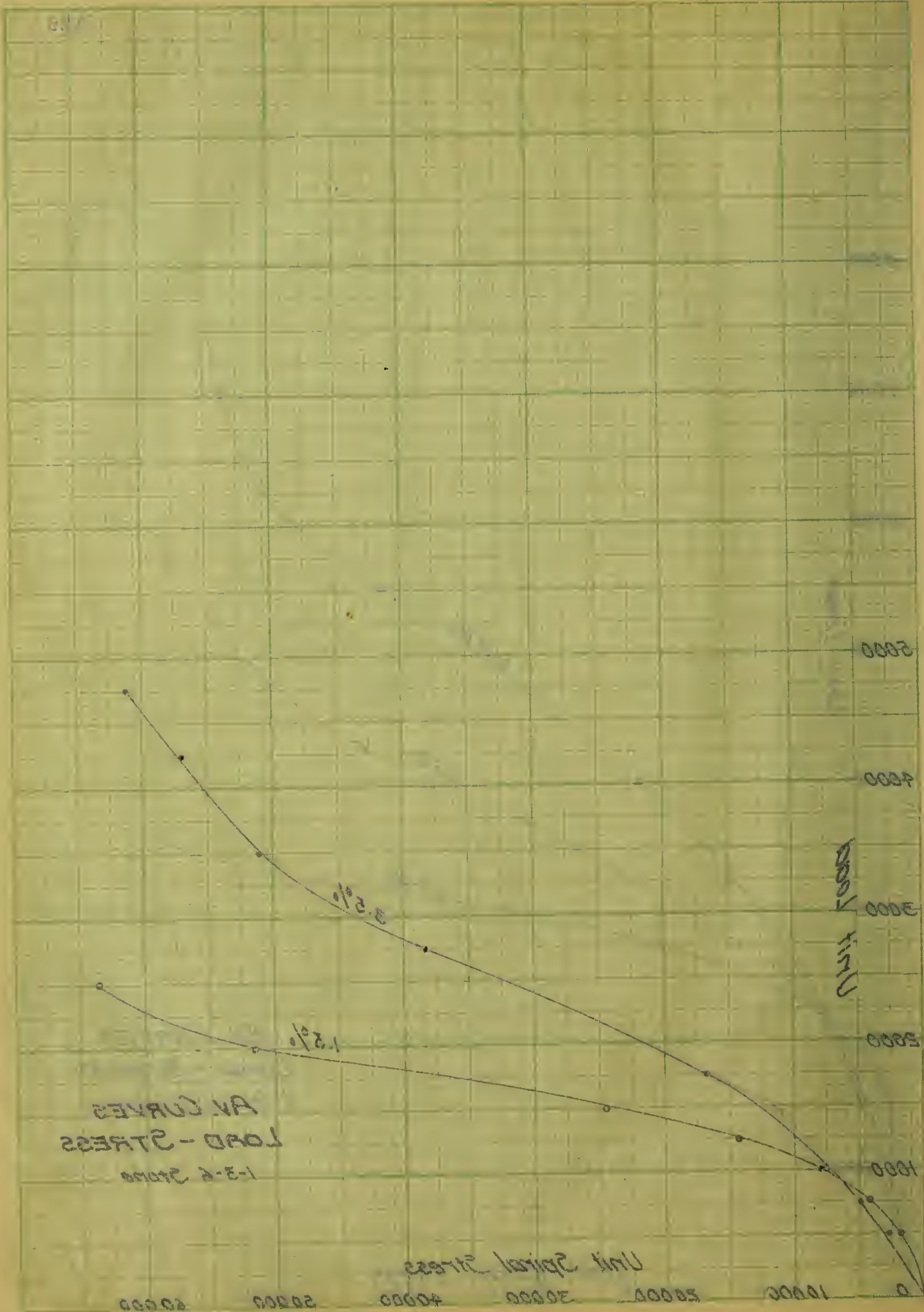
Av. Curves
Load - Stress
1-2-4 Stone
Unit Spiral Stress
Unit Load
6.0%
3.5%
1.5%
0
10000
20000
30000
40000
50000
60000
1000
2000
3000
4000
5000
6000

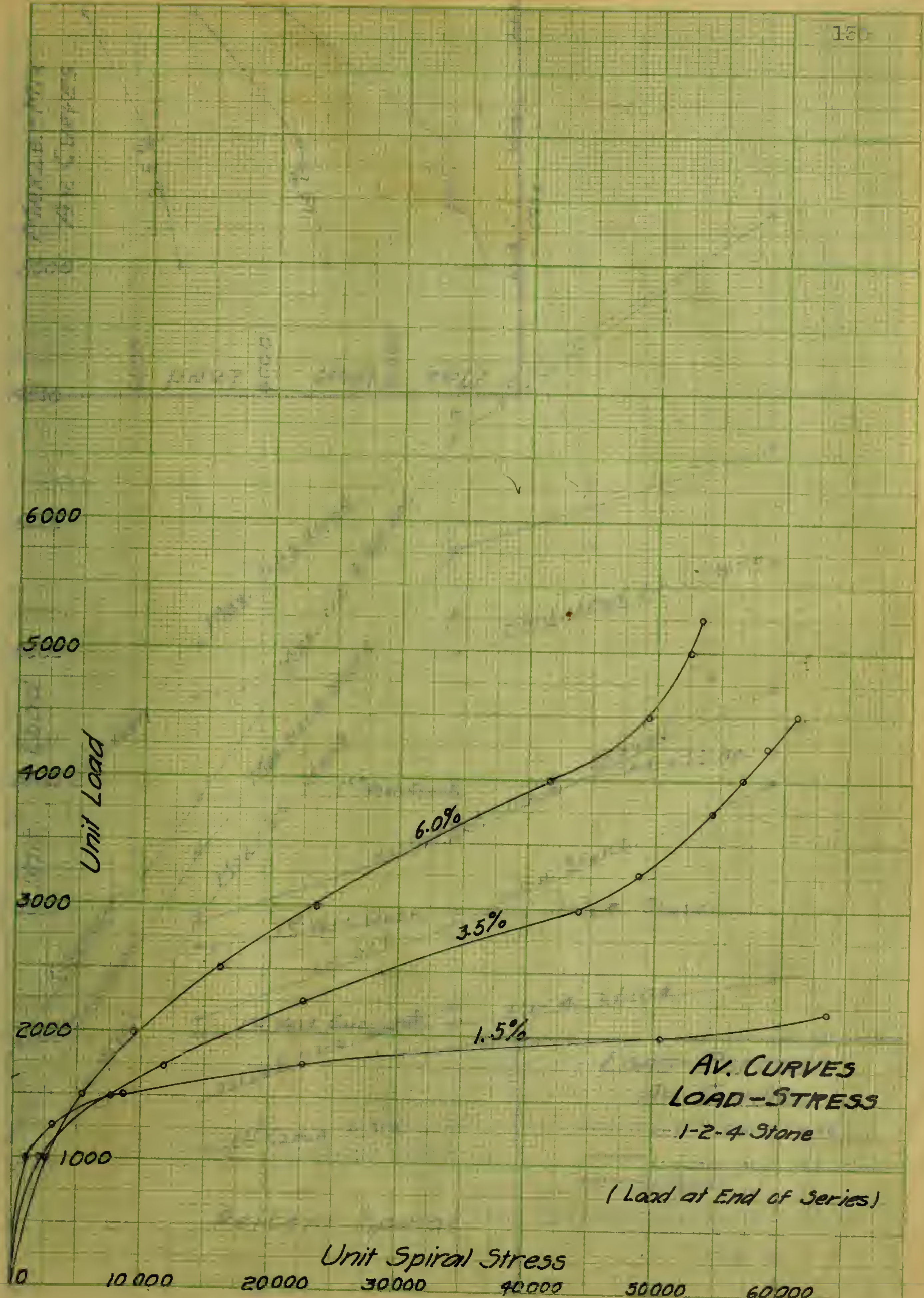


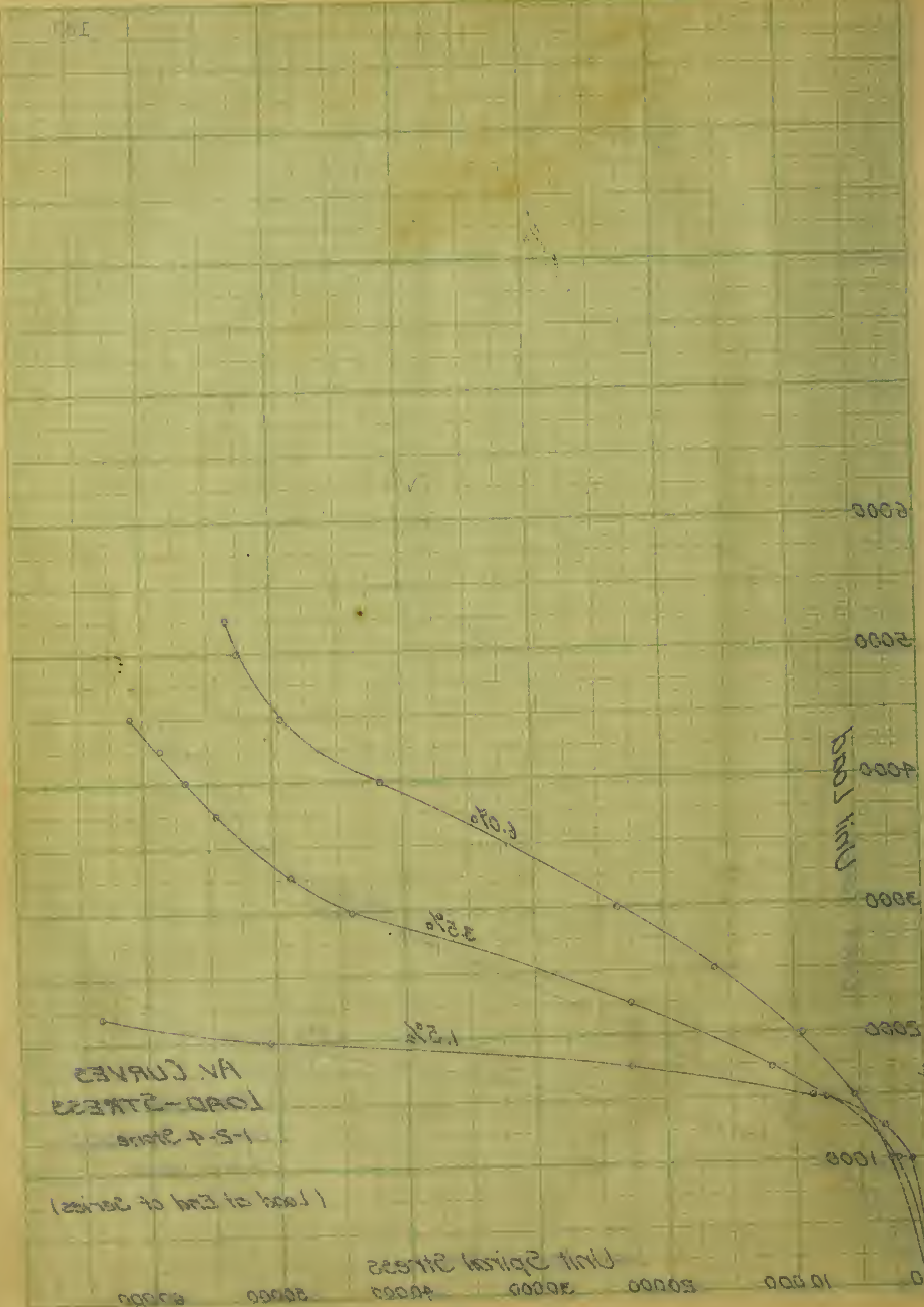
Unit Load
8000
7000
6000
5000
4000
3000
2000
1000
0
10000
20000
30000
40000
50000
Unit Spiral Stress
6.0%
3.5%
1.5%
Av. Curves
Load - Stress
1-2-4 Gravel


Ax. Curves
Load - Stress
1-2-4 Gravel
Unit Load
Unit Spiral Stress
6.0%
3.5%
1.5%
0
1000
2000
3000
4000
5000
6000
7000
8000
10000
20000
30000
40000
50000

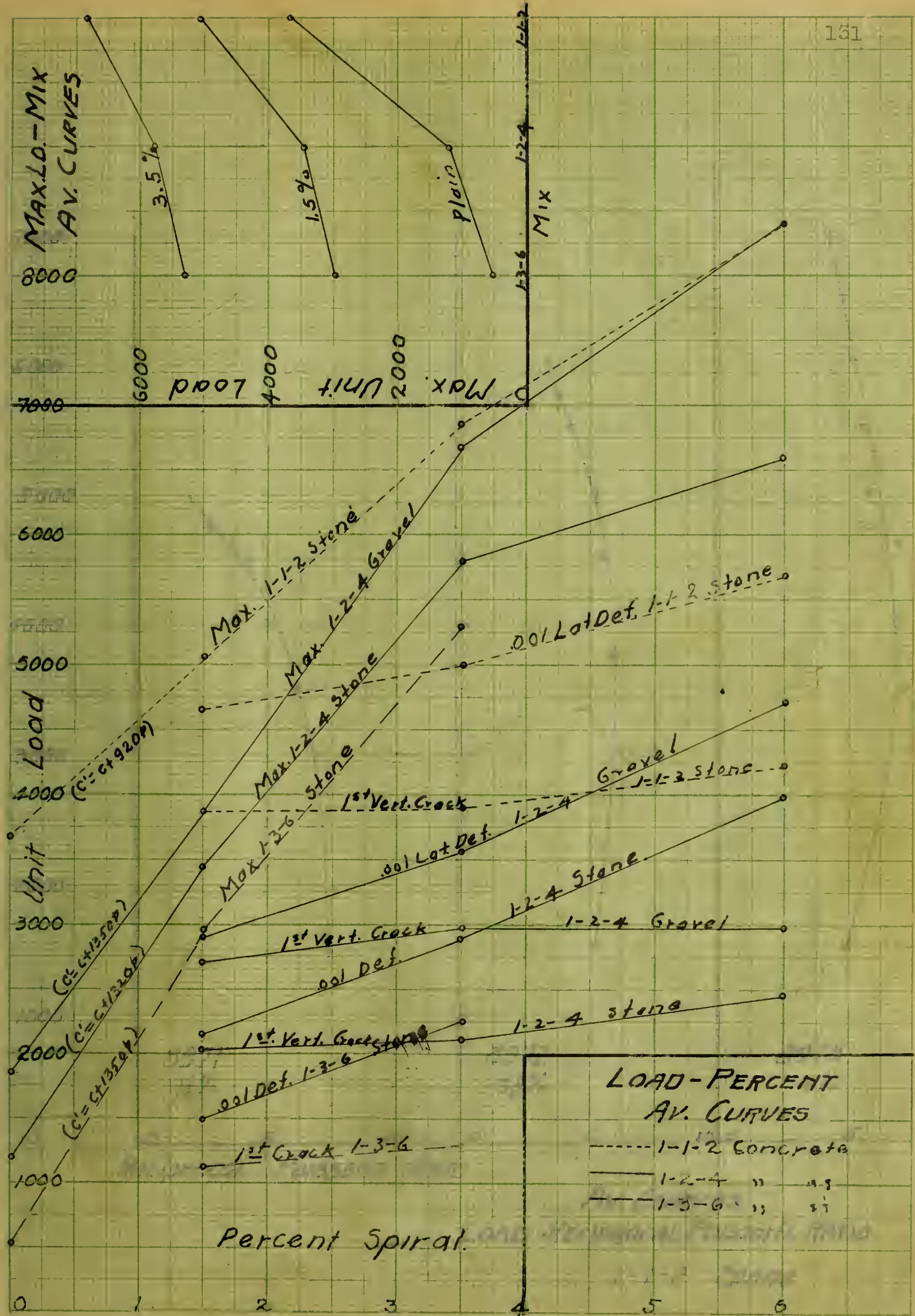

5000
4000
3000
2000
1000
Unit Load
3.5%
1.5%
AV. CURVES
LOAD - STRESS
1-3-6 Stone
Unit Spiral Stress
0
10000
20000
30000
40000
50000
60000


Av. CURVES
LOAD - STRESS
1-3-6 Stone
3.5%
1.5%
Unit Load
Unit Spiral Stress
0
1000
2000
3000
4000
5000
10000
20000
30000
40000
50000
60000

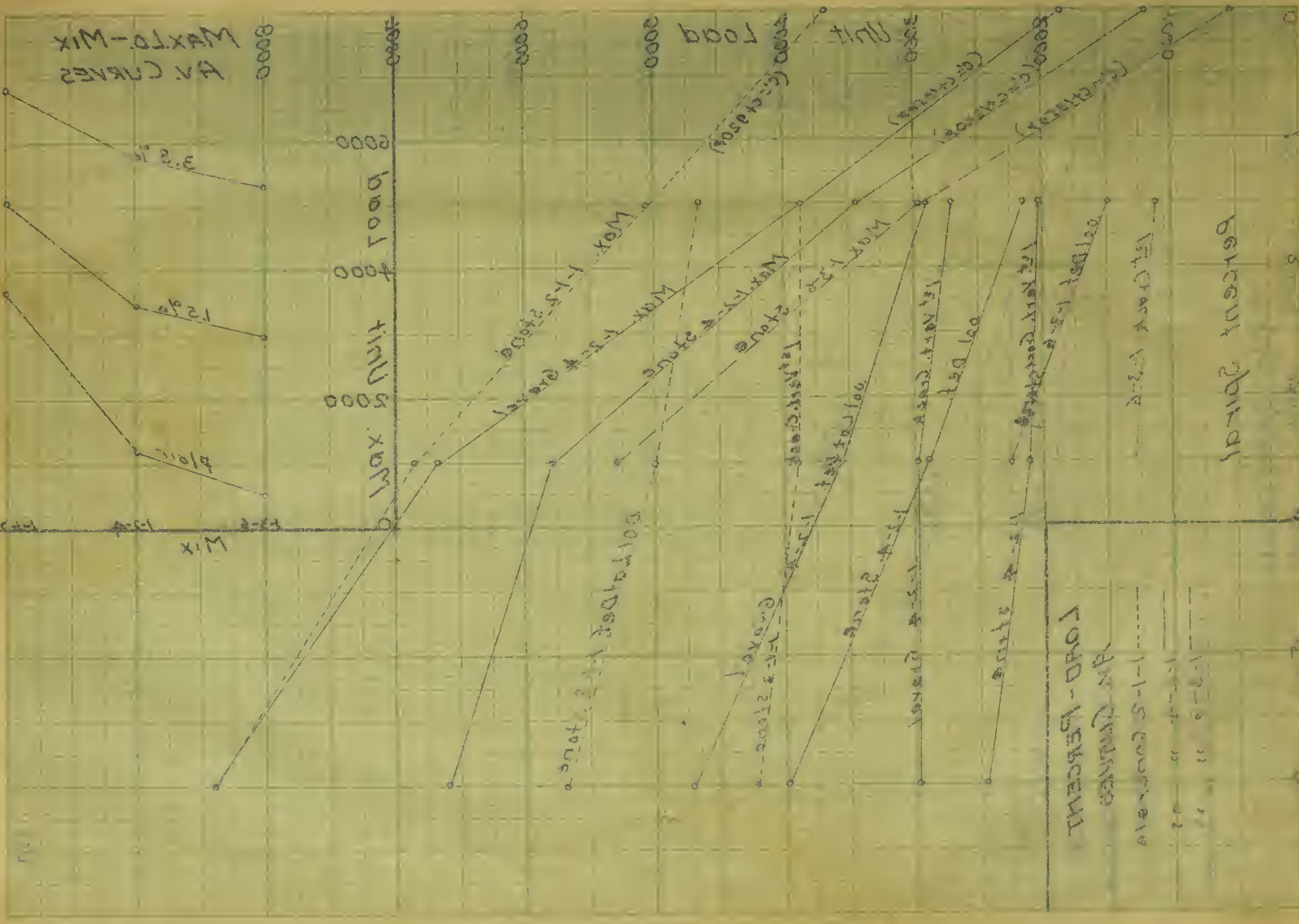

Av. Curves
Load-Stress
1-2-4 Stone
(Load at End of Series)
Unit Load
Unit Spiral Stress
6.0%
3.5%
1.5%
6000
5000
4000
3000
2000
1000
0
10000
20000
30000
40000
50000
60000



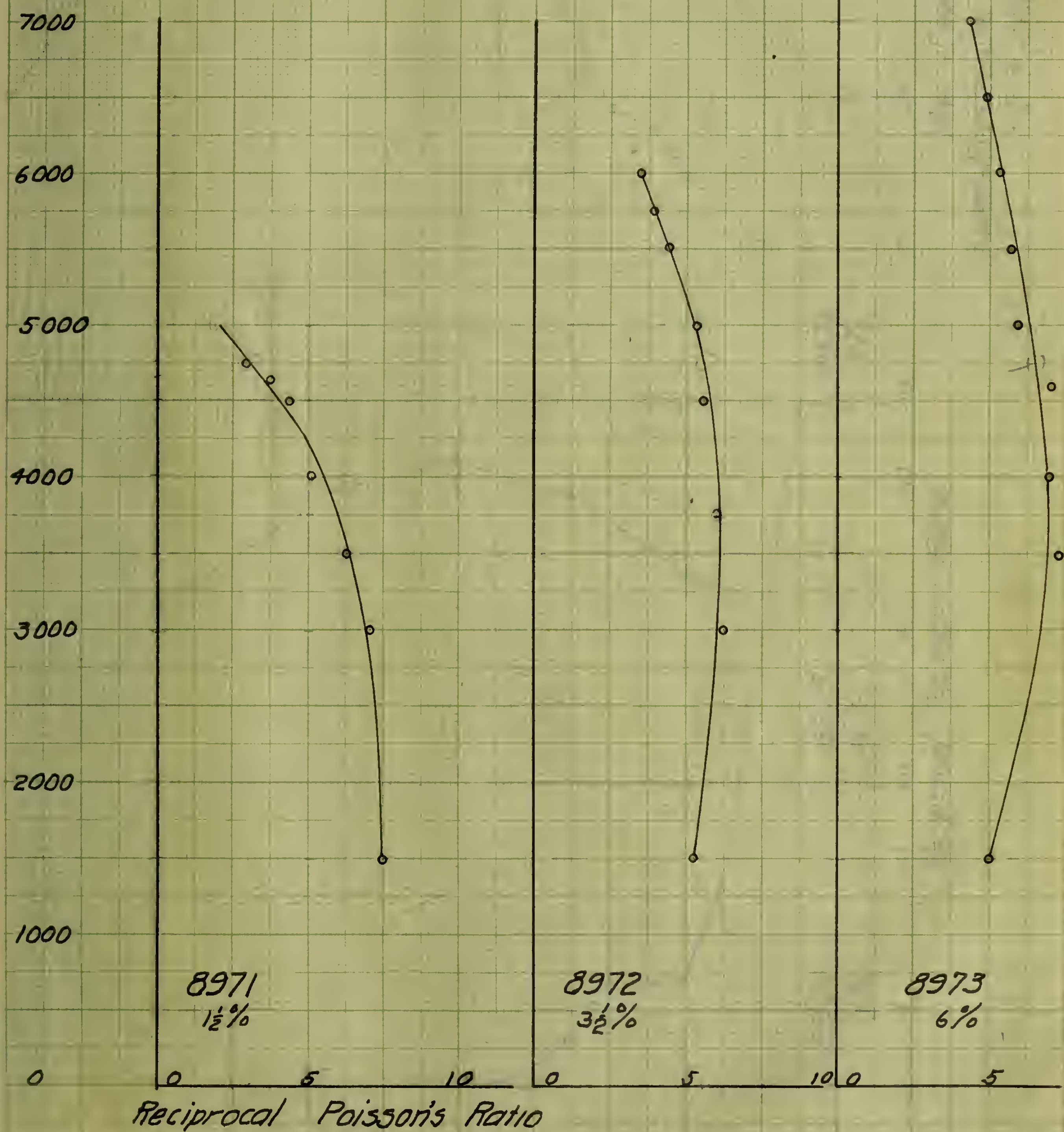
Av. Curves
Load-Stress
1-2-4 Stone
(Load at End of Series)
Unit Spiral Stress
Unit Load
6.0%
3.5%
1.5%
0
10 000
20000
30000
40000
50000
60000
1000
2000
3000
4000
5000
6000



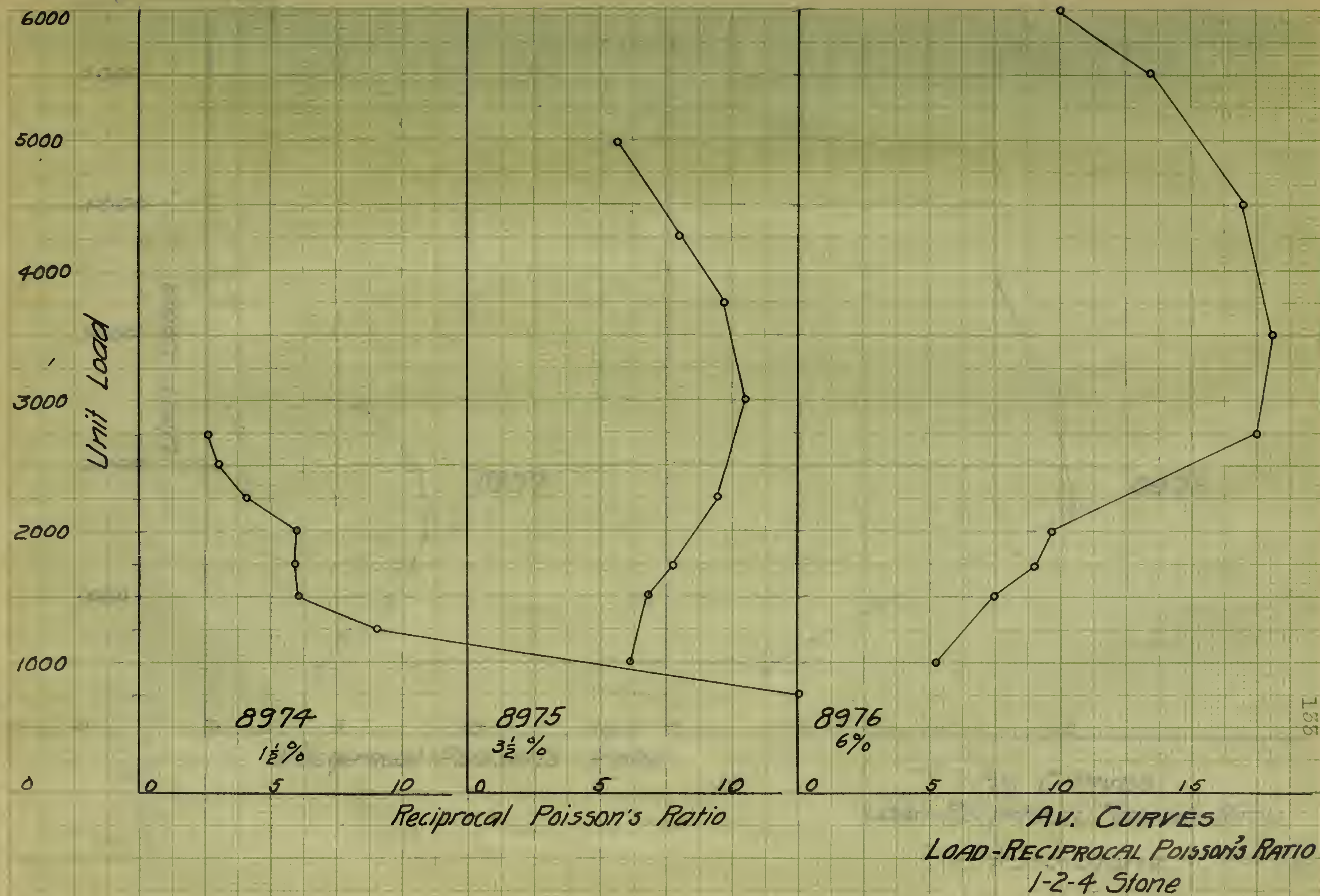
Max. Ld.-Mix Av. Curves
3.5%
1.5%
plain
Mix
1-1-2
1-2-4
1-3-6
8000
6000
4000
2000
Max Unit Load
7000
6000
5000
4000
3000
2000
1000
Unit Load
Max. 1-1-2 Stone
Max. 1-2-4 Gravel
Max. 1-2-4 Stone
Max. 1-3-6 Stone
.001 Lat Def. 1-1-2 Stone
(c'=c+920p)
1st Vert. Crack
1-1-2 Stone
Gravel
.001 Lat Def. 1-2-4
1-2-4 Stone.
(c'=c+1350p)
(c'=c+1320p)
(c'=c+1350p)
1st Vert. Crack
1-2-4 Gravel
.001 Def.
1-2-4 stone
1st Vert. Crack Stone
.001 Def. 1-3-6
1st Crack 1-3-6
Percent Spiral.
0
1
2
3
4
5
6
LOAD-PERCENT AV. CURVES
1-1-2 Concrete
1-2-4 " "
1-3-6 " "

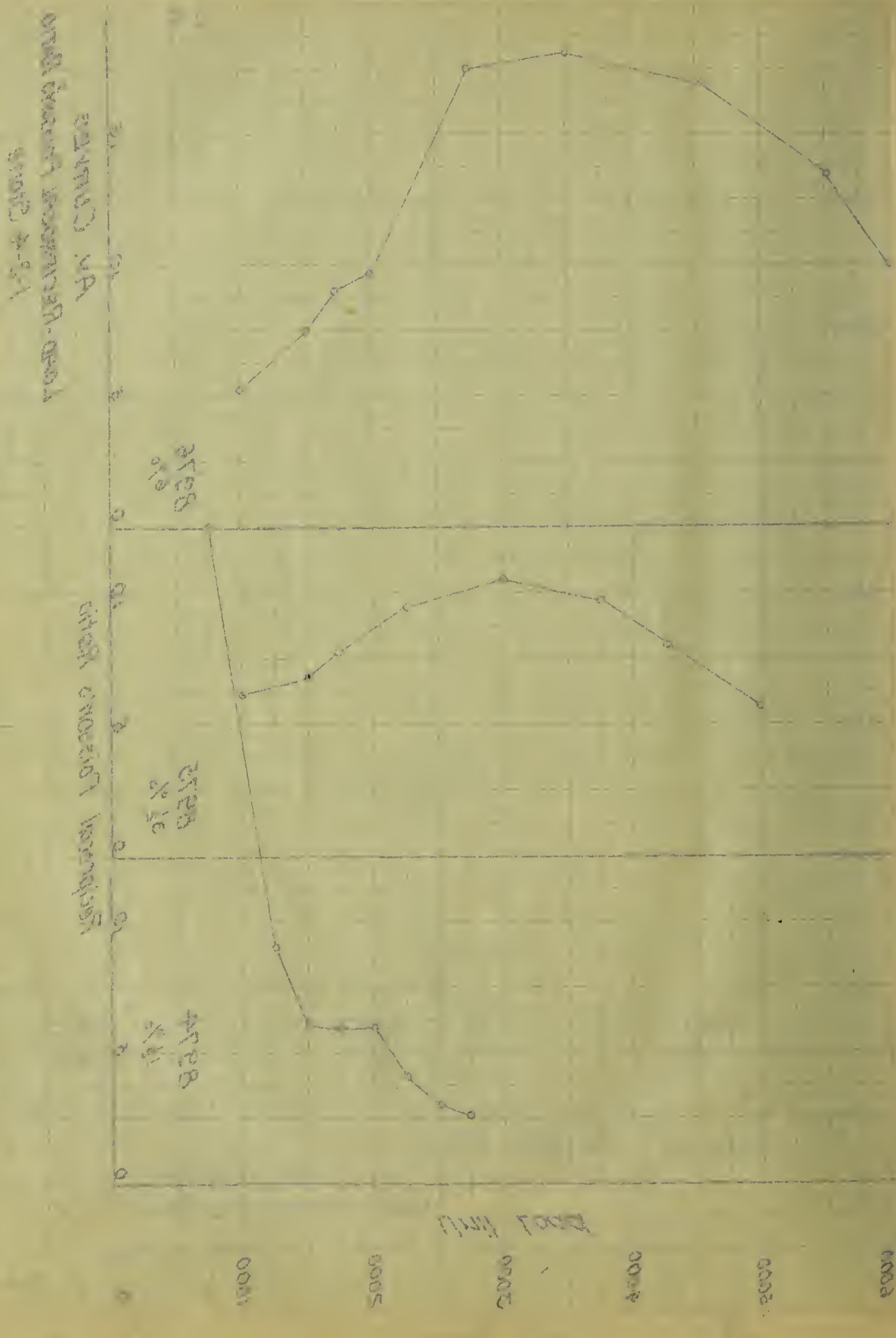


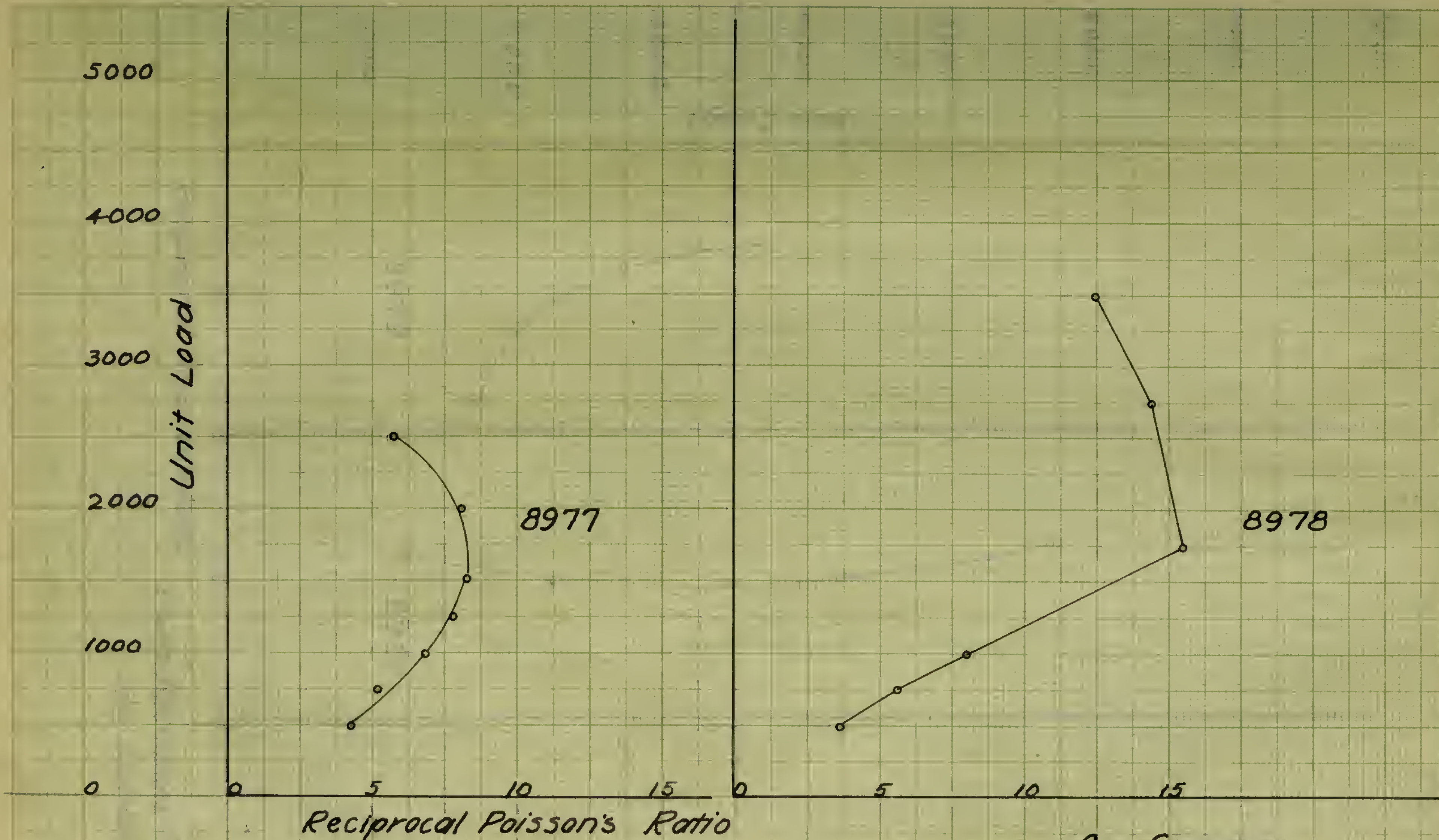
Max. Unit Load
Unit Load
Percent Spiral
Mix



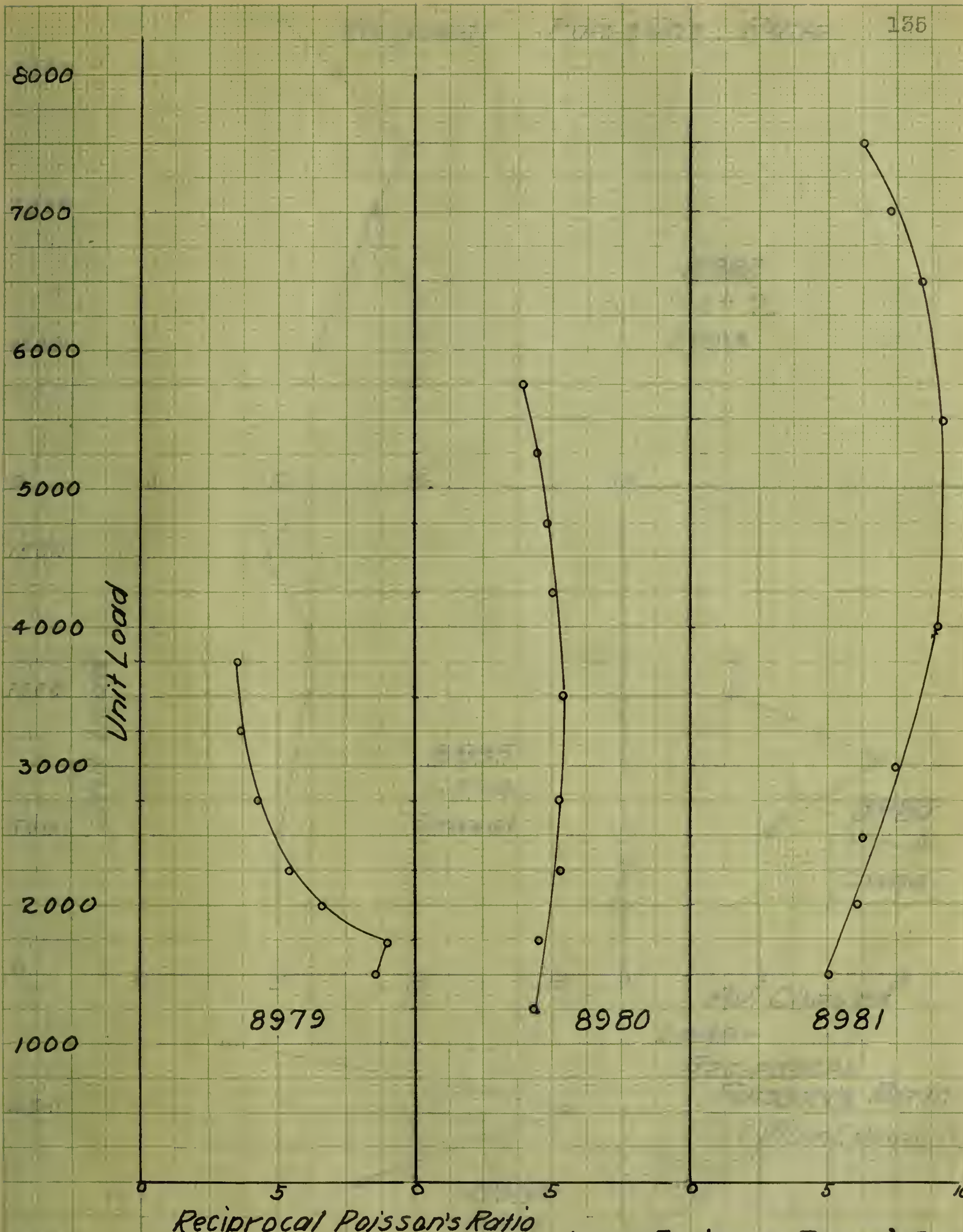
AV. CURVES
LOAD - RECIPROCAL POISSON'S RATIO
1-1-2 Stone


6000
5000
4000
3000
2000
1000
0
Unit Load
8974
1½%
8975
3½ %
8976
6%
0
5
10
0
5
10
0
5
10
15
Reciprocal Poisson's Ratio
Av. Curves
Load-Reciprocal Poisson's Ratio
1-2-4 Stone

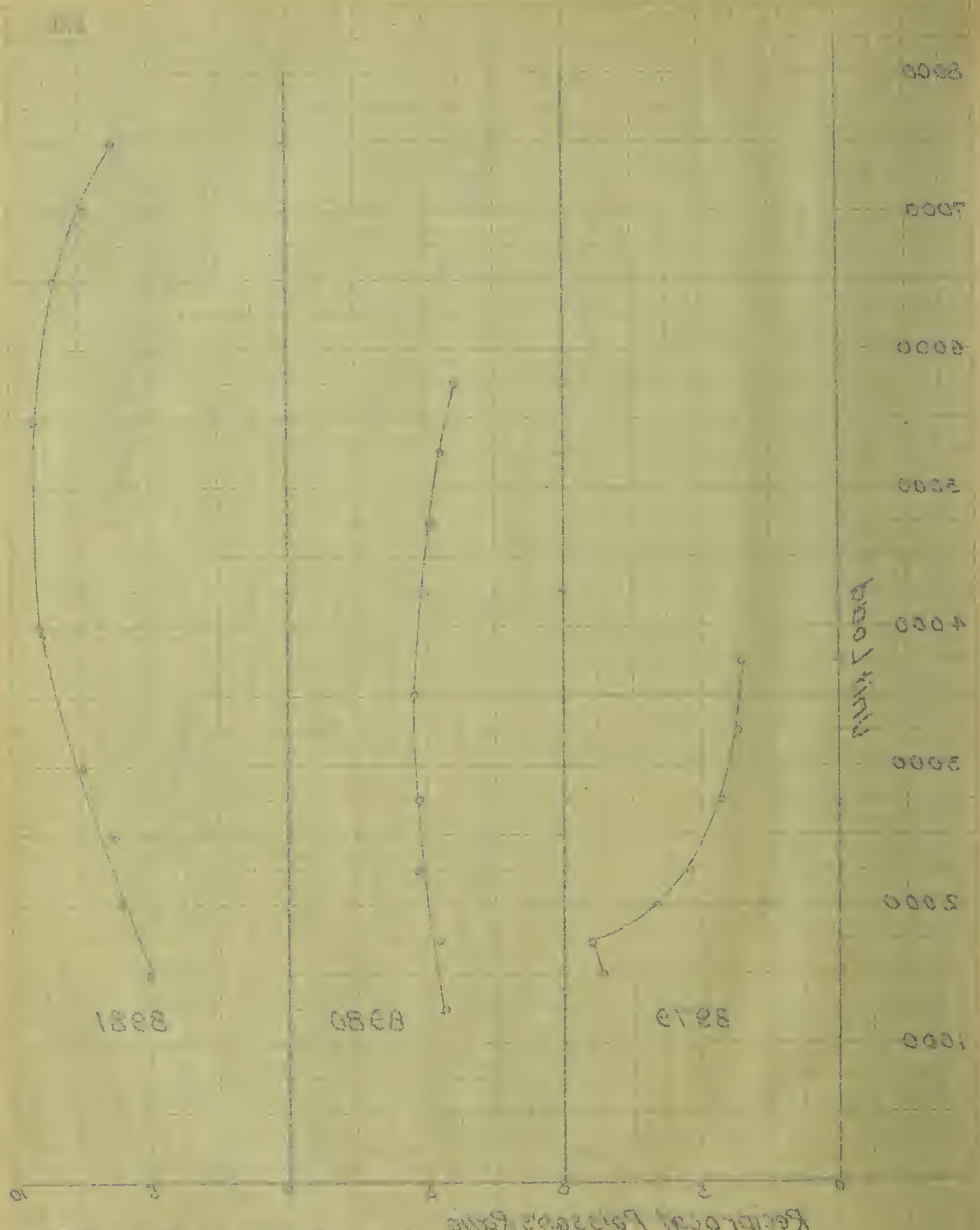




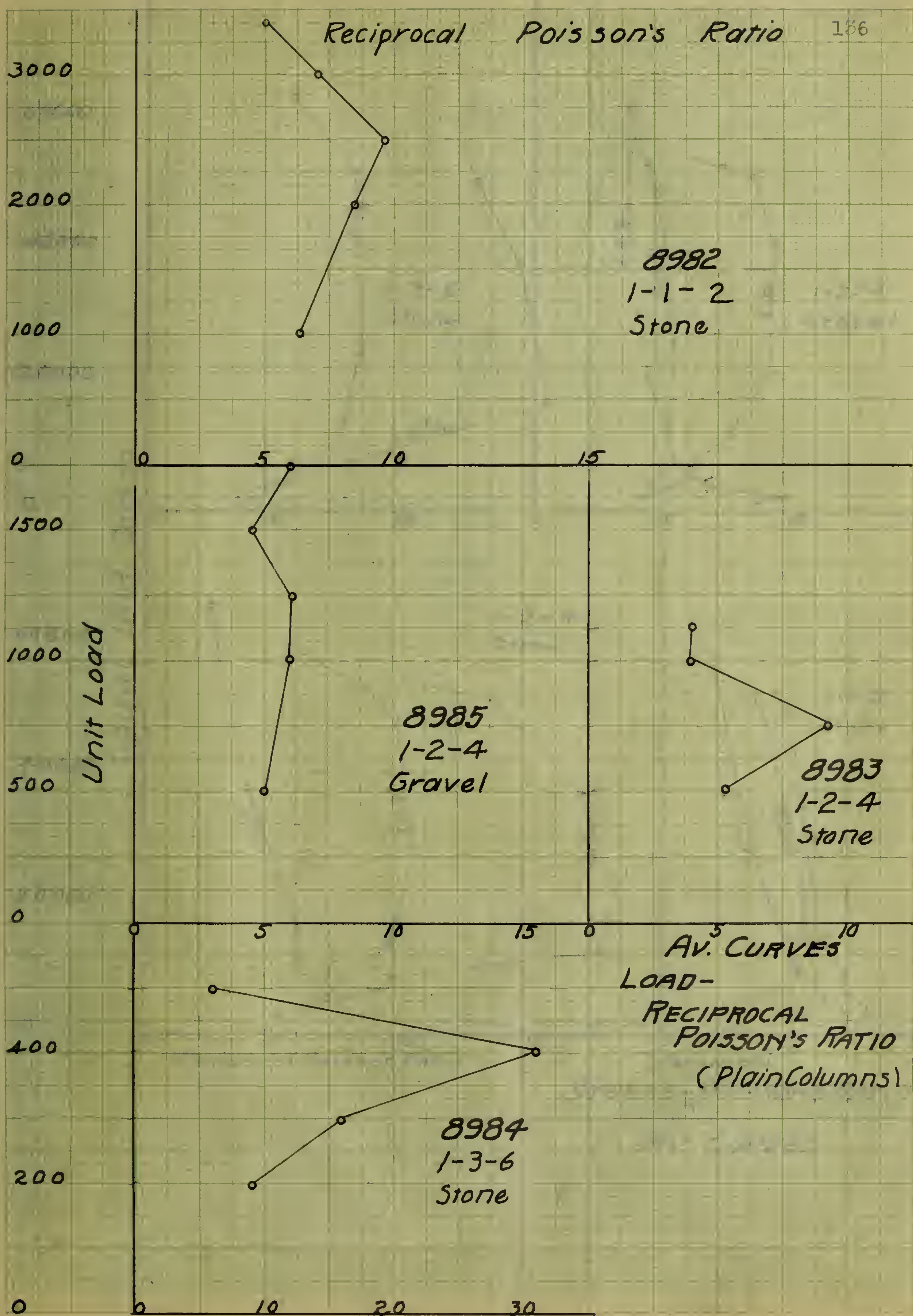
Av. CURVES
LOAD-RECIPROCAL POISSON'S RATIO
1-3-6 Stone.

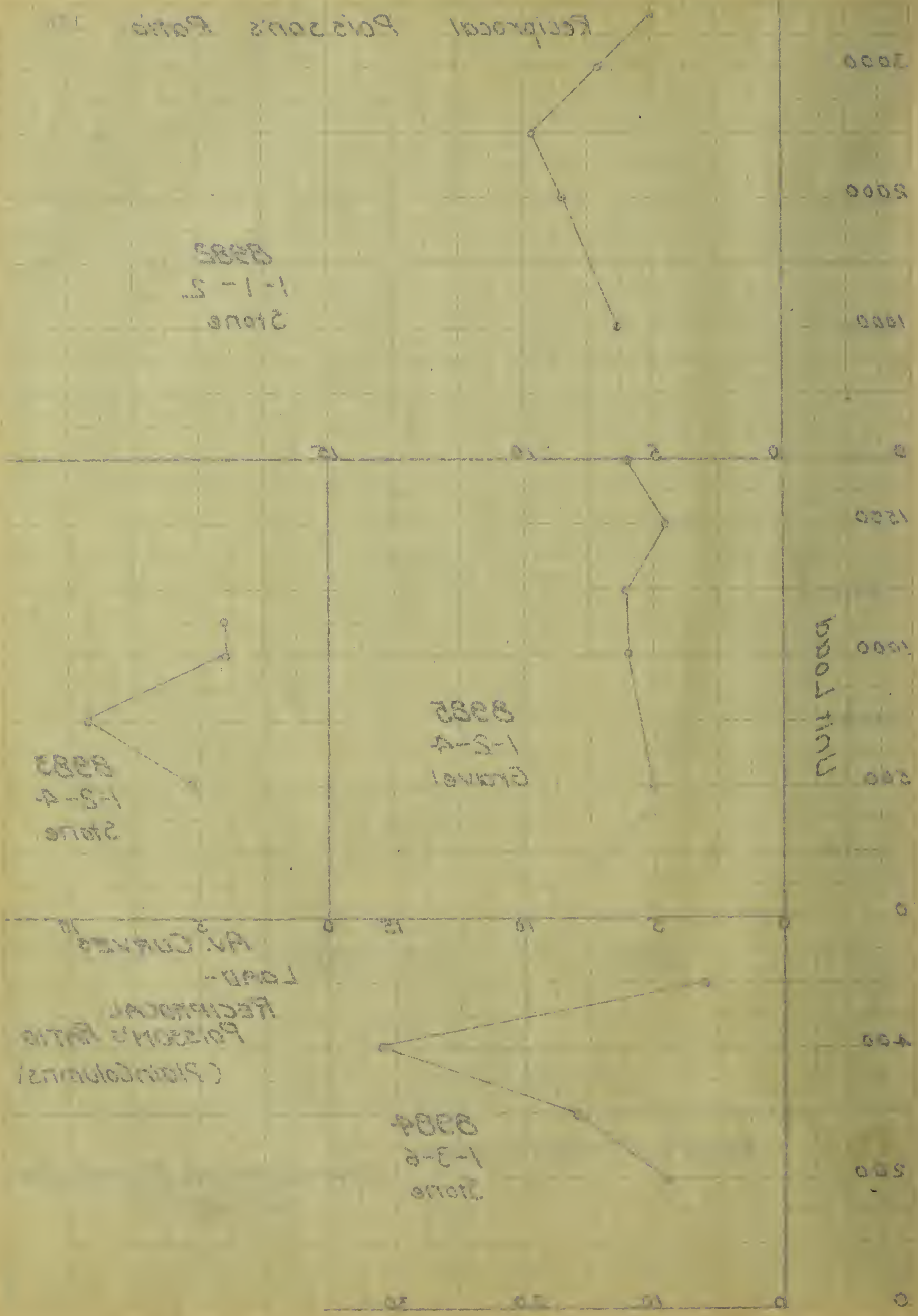


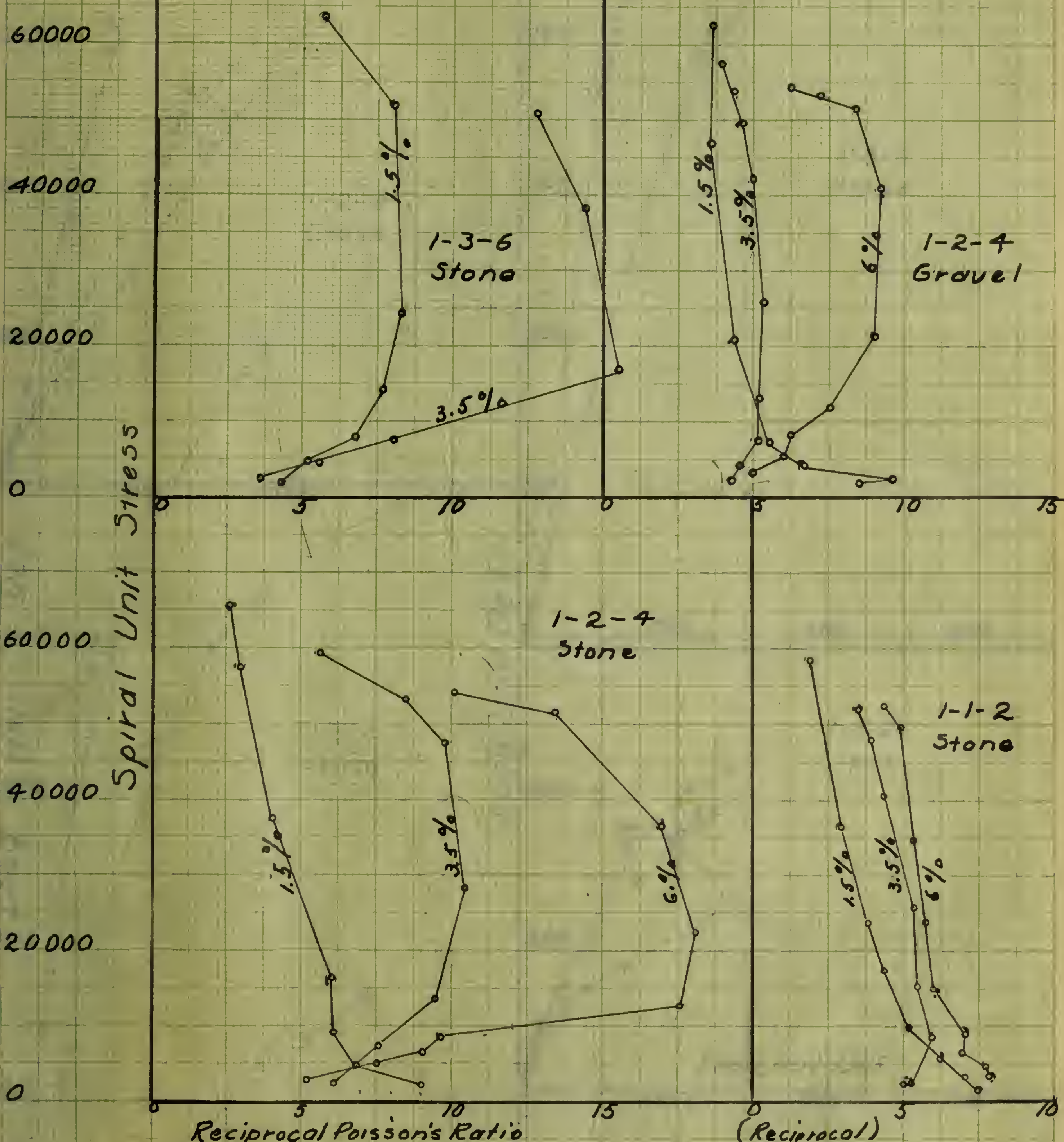
LOAD-RECIROCAL POISSON'S RATIO
AV. CURVES



Unit Load
8000
7000
6000
5000
4000
3000
2000
1000
8979
8980
8981
0
5
0
5
0
5
10
Reciprocal Poisson's Ratio
Load-Reciprocal Poisson's Ratio Curves

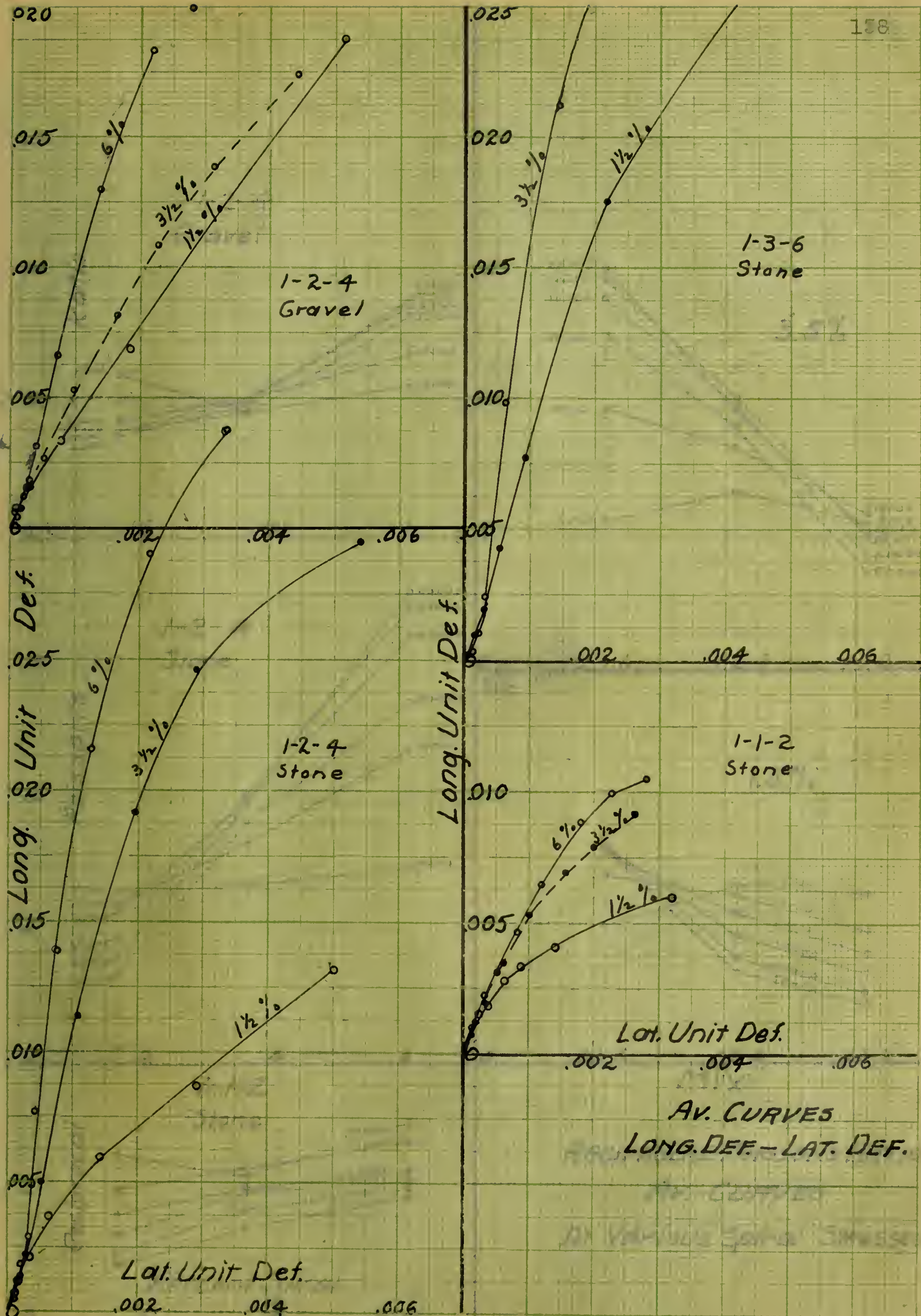

Reciprocal Poisson's Ratio
3000
2000
1000
0
8982
1-1-2
Stone
0
5
10
15
1500
1000
500
Unit Load
8985
1-2-4
Gravel
8983
1-2-4
Stone
Av. Curves
Load-
Reciprocal
Poisson's Ratio
(Plain Columns)
400
200
8984
1-3-6
Stone
20
30

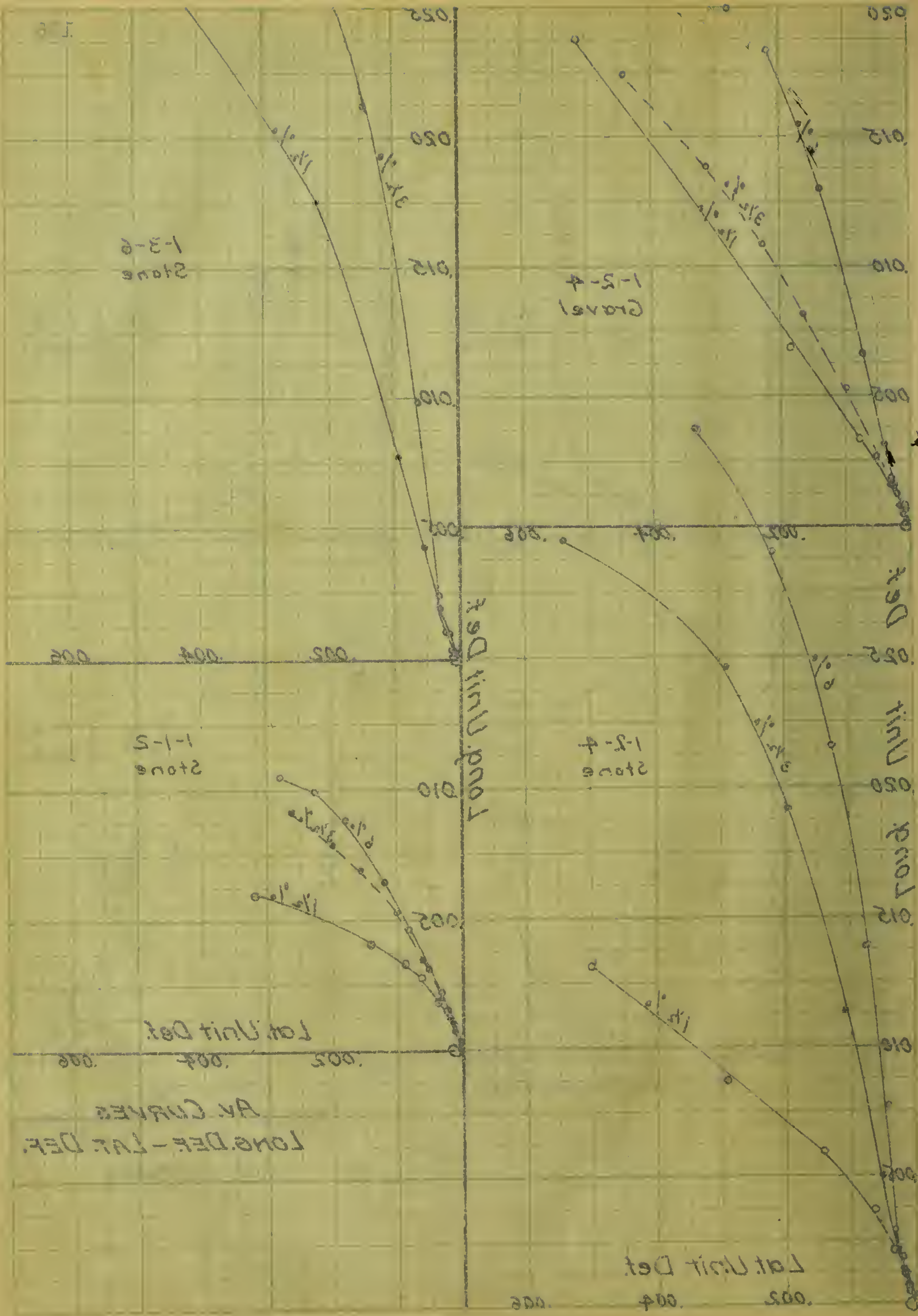

Reciprocal Poisson's Ratio
8982
1-1-2
Stone
8985
1-2-4
Gravel
8983
1-2-4
Stone
8984
1-3-6
Stone
Av. Curves
Load-
Reciprocal
Poisson's Ratio
(Plain Columns)
Unit Load

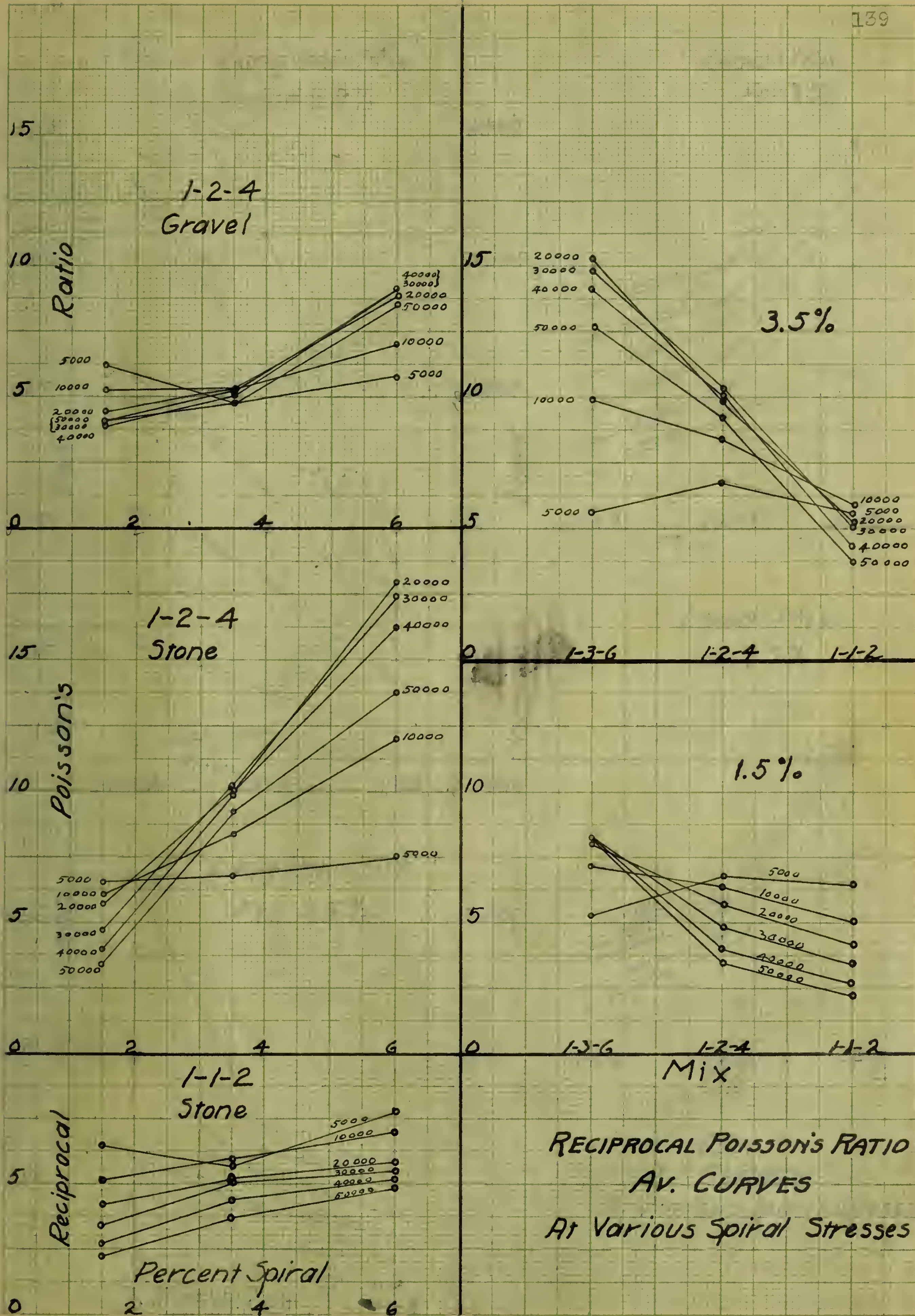


STRESS - POISSON'S RATIO

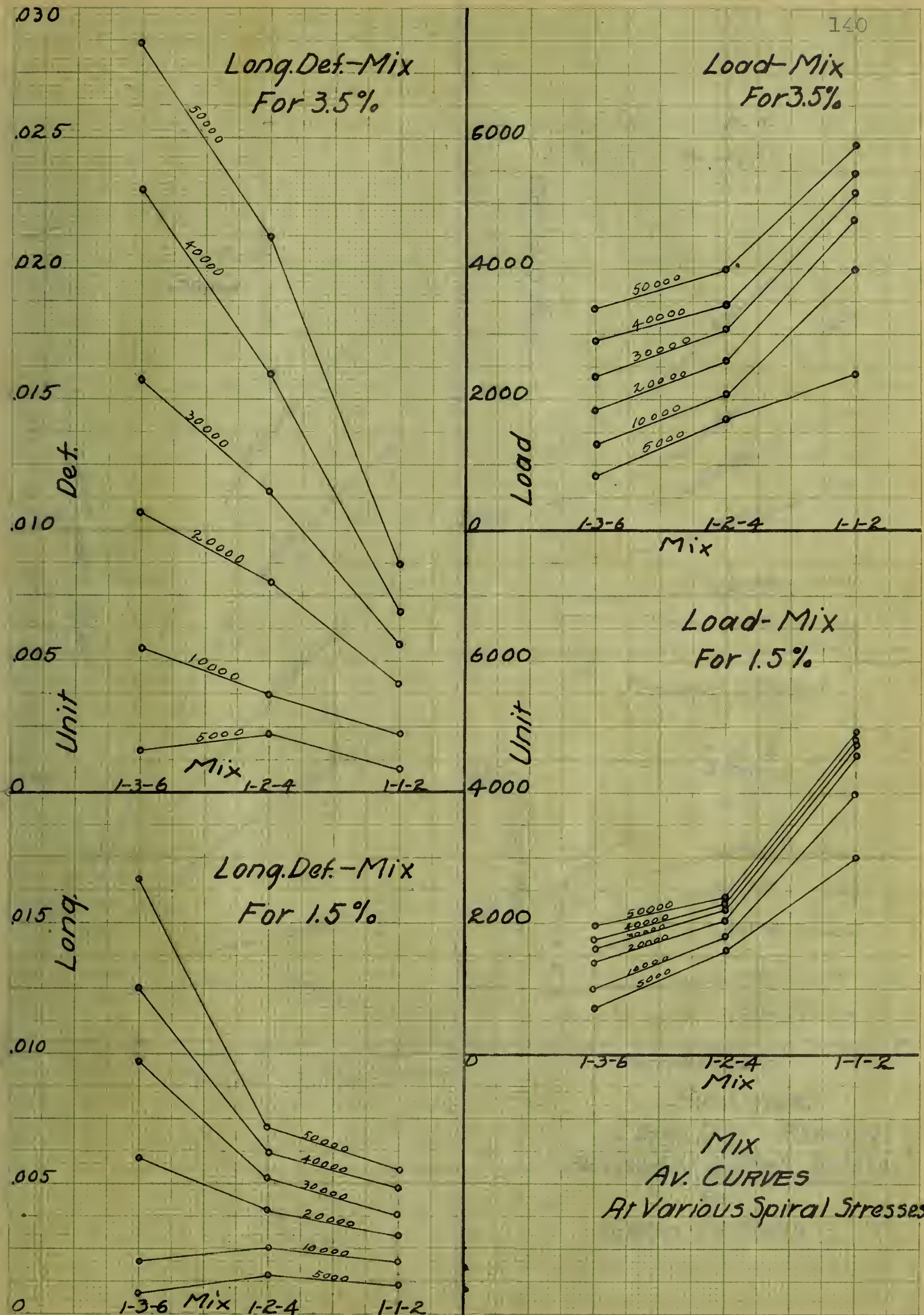
AV. CURVES

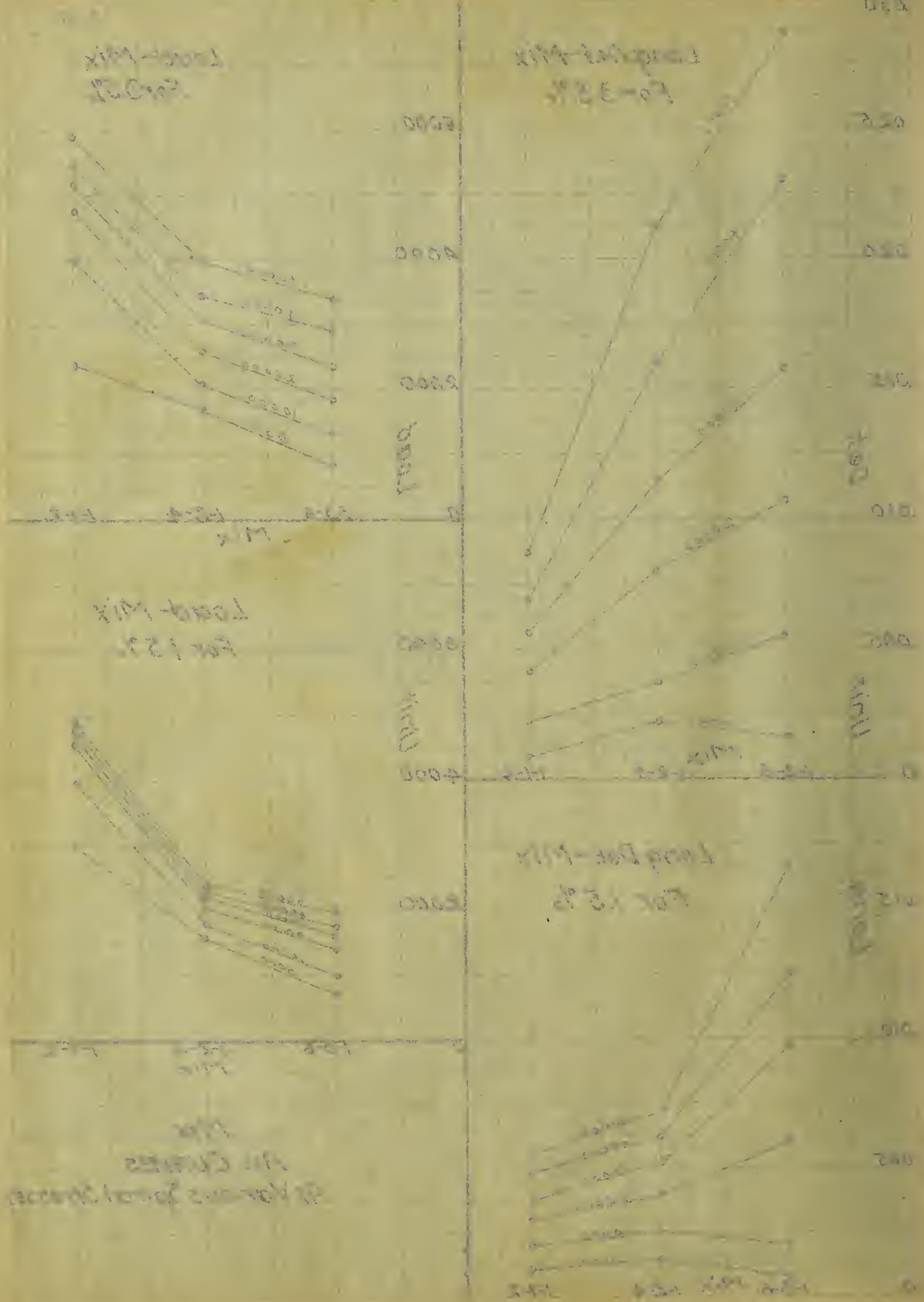

1-2-4
Gravel
6%
3½%
1½%
1-3-6
Stone
3½%
1½%
1-2-4
Stone
6%
3½%
1½%
1-1-2
Stone
6%
3½%
1½%
Long. Unit Def.
Lat. Unit Def.
.002
.004
.006
.005
.010
.015
.020
.025
Av. Curves
Long. Def. - Lat. Def.

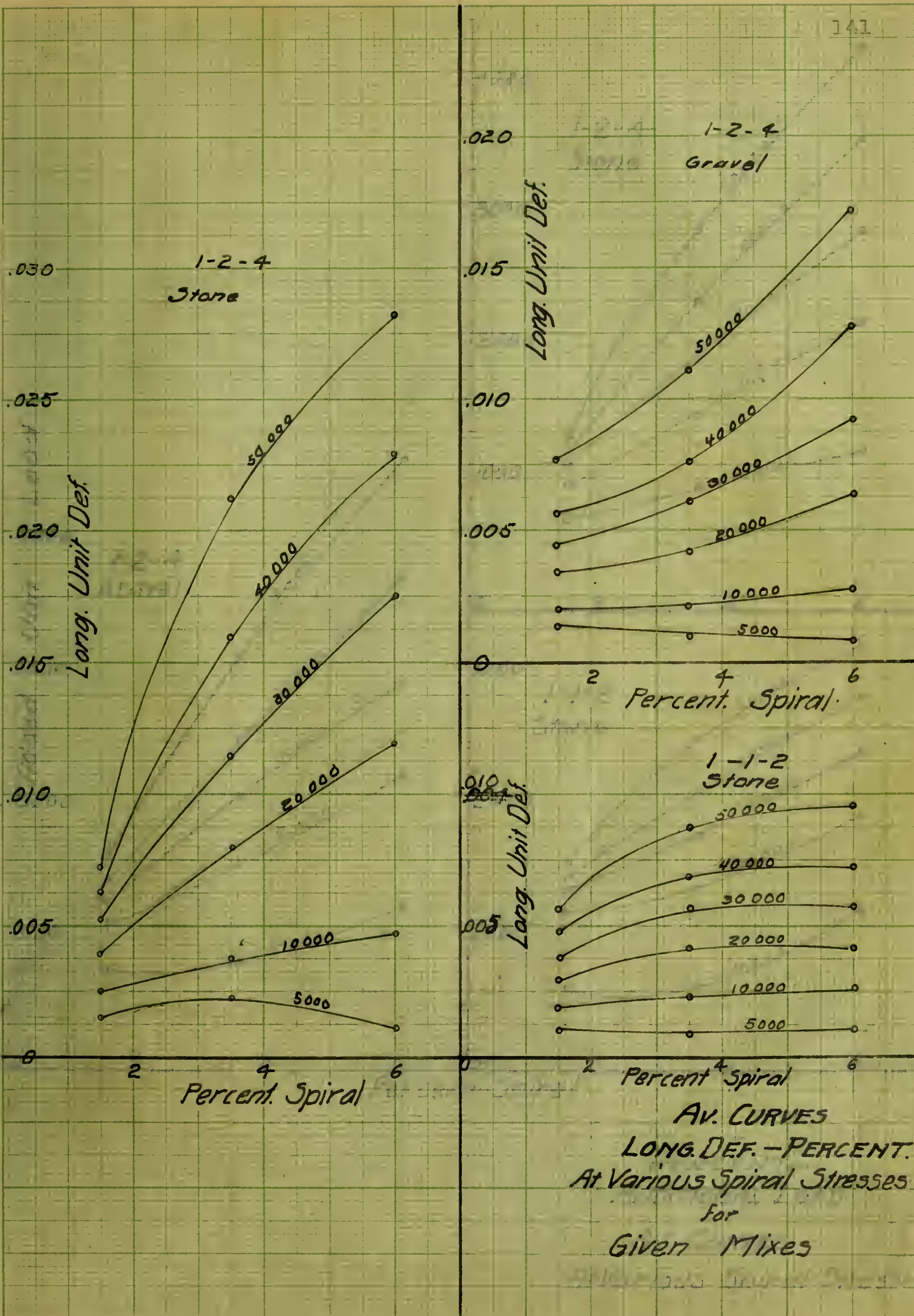

Av. Curves
Long. Def. - Lat. Def.
1-3-6
Stone
1-2-4
Gravel
1-1-2
Stone
1-2-4
Stone
Long. Unit Def.
Lat. Unit Def.



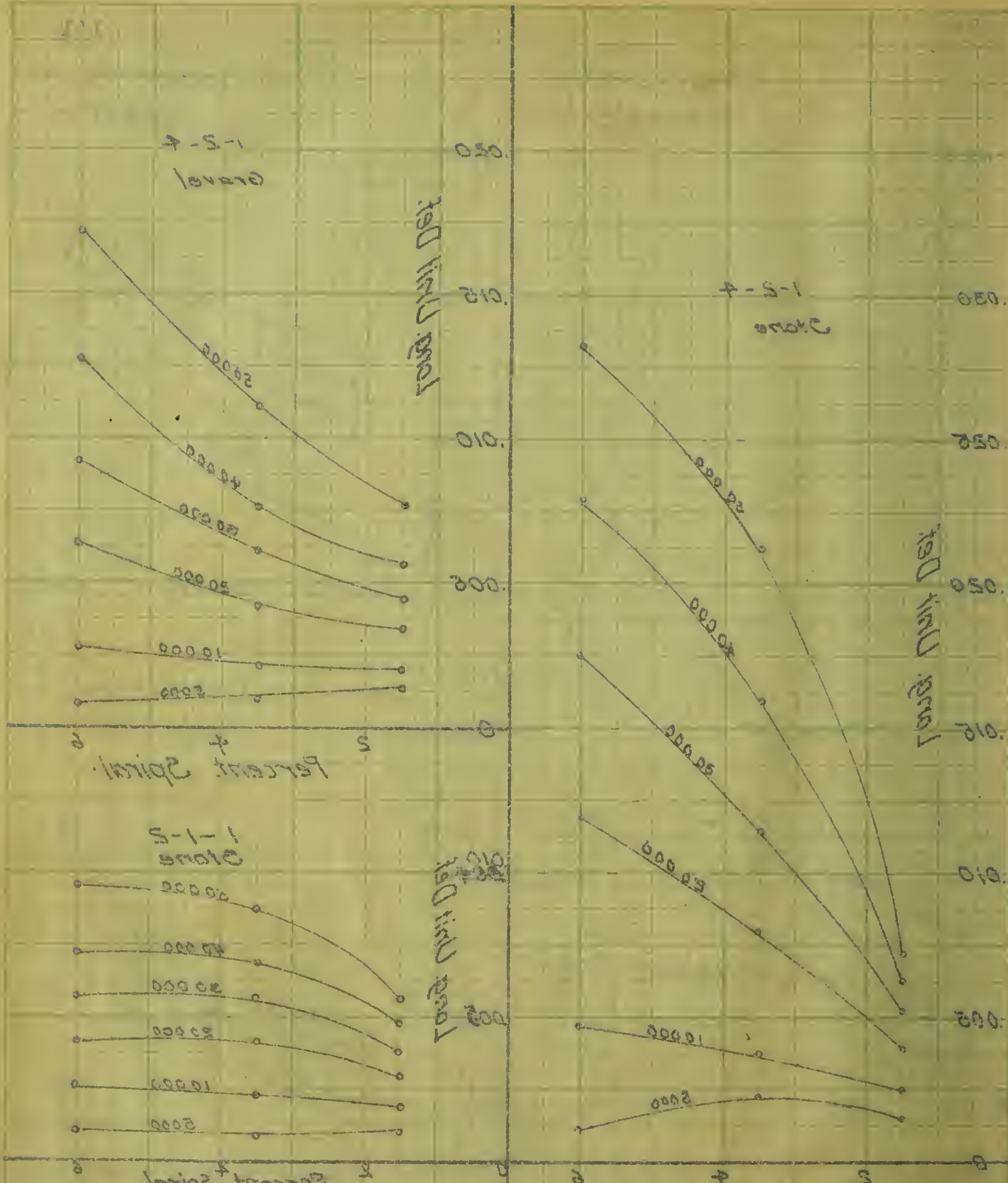
RECIPROCAL POISSON'S RATIO
AV. CURVES
At Various Spiral Stresses


Long. Def.-Mix
For 3.5%
Unit Long. Def.
.030
.025
.020
.015
.010
.005
0
50000
40000
30000
20000
10000
5000
Mix
1-3-6
1-2-4
1-1-2
Load-Mix
For 3.5%
Load
6000
4000
2000
0
Long. Def.-Mix
For 1.5%
.015
.010
.005
Load-Mix
For 1.5%
Unit
Mix
Av. Curves
At Various Spiral Stresses

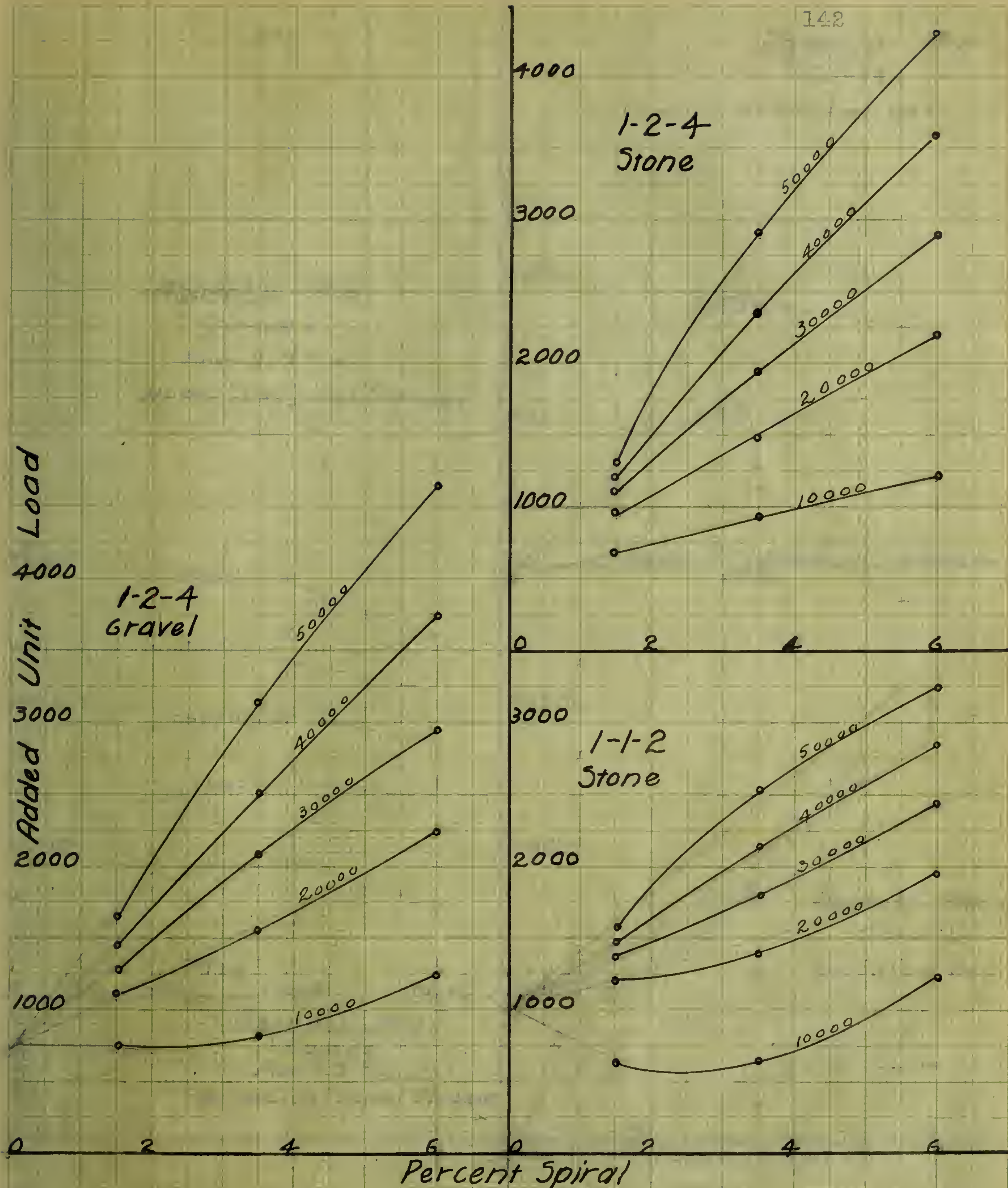




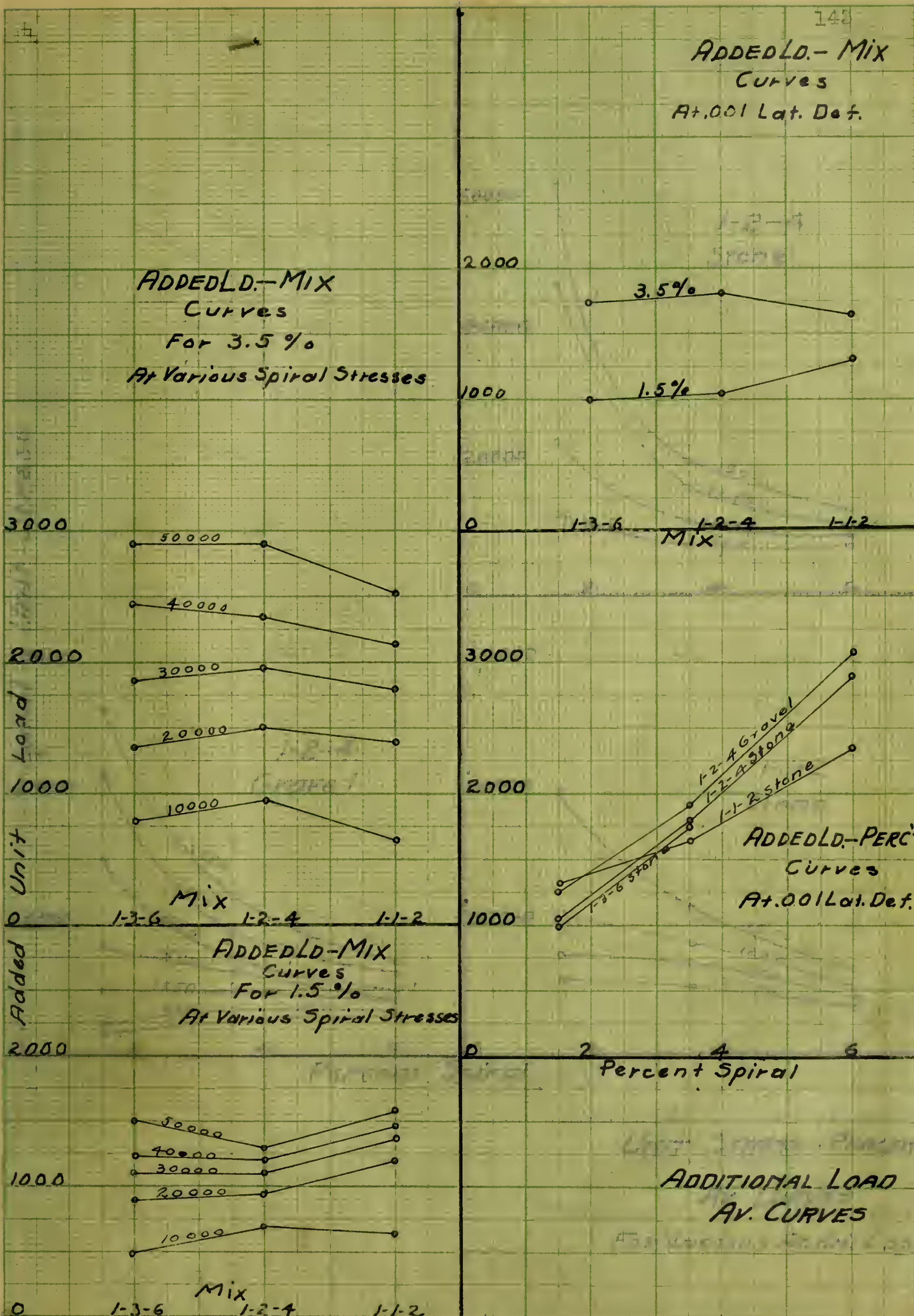
Av. CURVES
LONG. DEF. – PERCENT.
At Various Spiral Stresses
for
Given Mixes



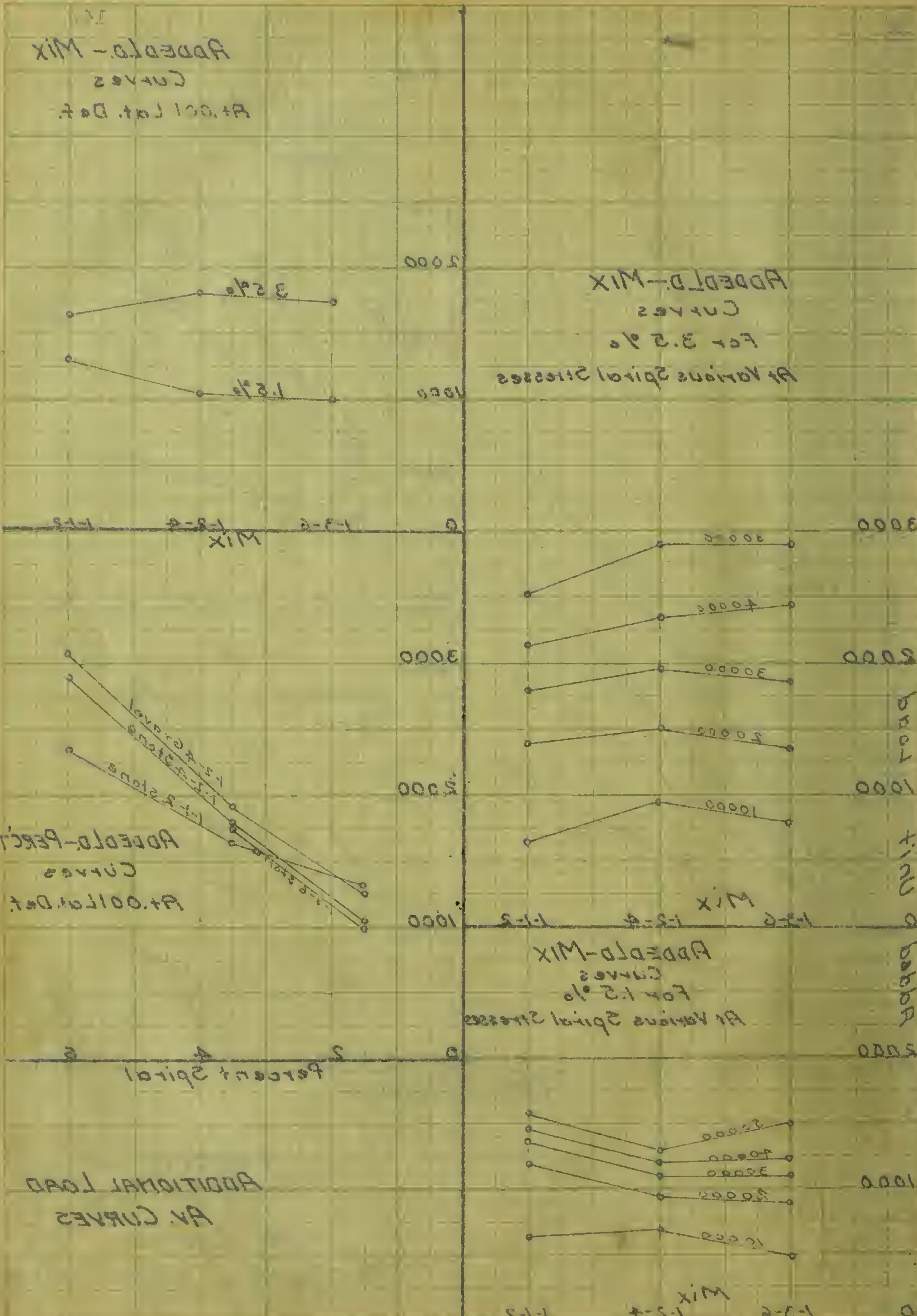
Ar Curves
Long Def - Percent
At Various Spiral Stresses
for
Given Mixes



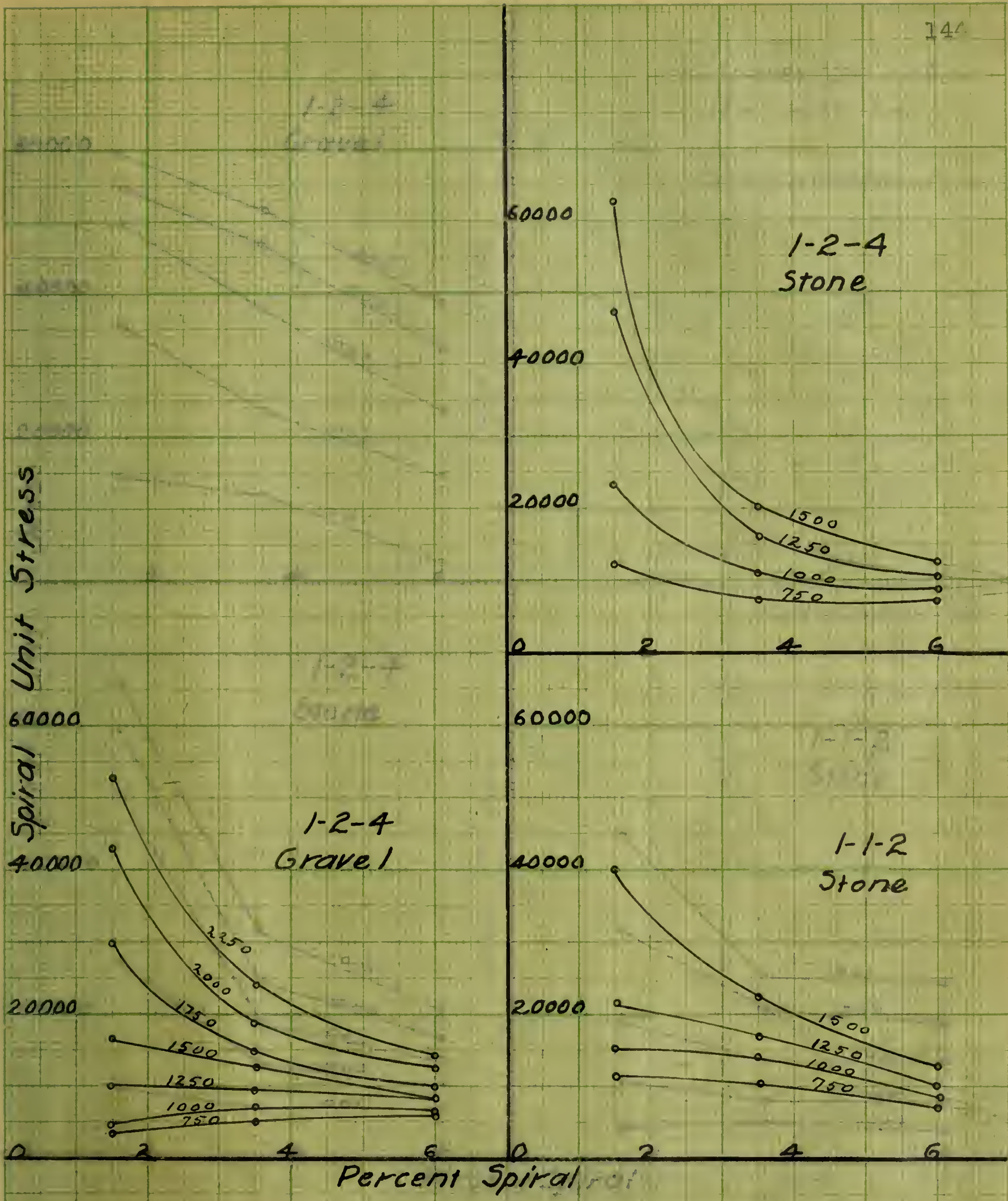
PERCENT—
ADDITIONAL LOAD
AV. CURVES
At Various Spiral Stresses



AddedLd.-Mix Curves At .001 Lat. Def.
2000
1000
0
3.5%
1.5%
1-3-6
1-2-4
1-1-2
Mix
AddedLd.-Mix Curves For 3.5% At Various Spiral Stresses
3000
2000
1000
0
50000
40000
30000
20000
10000
Mix
1-3-6
1-2-4
1-1-2
Added Unit Load
AddedLd.-Mix Curves For 1.5% At Various Spiral Stresses
2000
1000
0
50000
40000
30000
20000
10000
Mix
1-3-6
1-2-4
1-1-2
3000
2000
1000
0
1-2-4 Gravel
1-2-4 Stone
1-1-2 Stone
1-3-6 Stone
AddedLd.-Perc't. Curves At .001 Lat. Def.
2
4
6
Percent Spiral
Additional Load Av. Curves



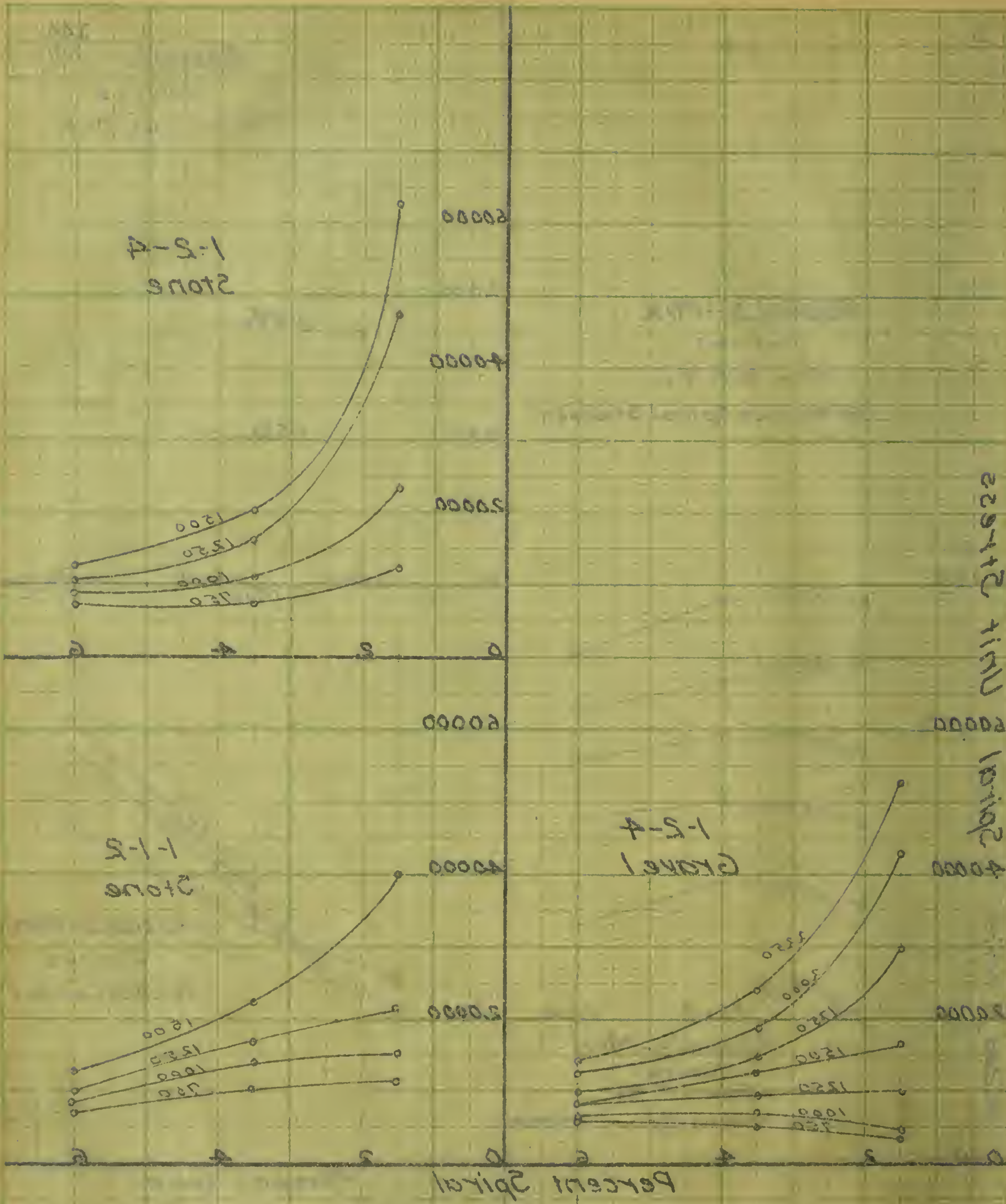
Added Load Av. Curves
Added Ld.-Mix Curves At .001 Lat. Def.
3.5%
1.5%
Mix
Added Ld.-Perc't. Curves At .001 Lat. Def.
1-2-4 Gravel
1-2-4 Stone
1-1-2 Stone
1-3-6 Stone
Percent Spiral
Added Ld.-Mix Curves For 3.5% At Various Spiral Stresses
50000
40000
30000
20000
10000
Added Ld.-Mix Curves For 1.5% At Various Spiral Stresses
Added Load Unit
1-1-2
1-2-4
1-3-6



UNIT STRESS - PERCENT

AV. CURVES

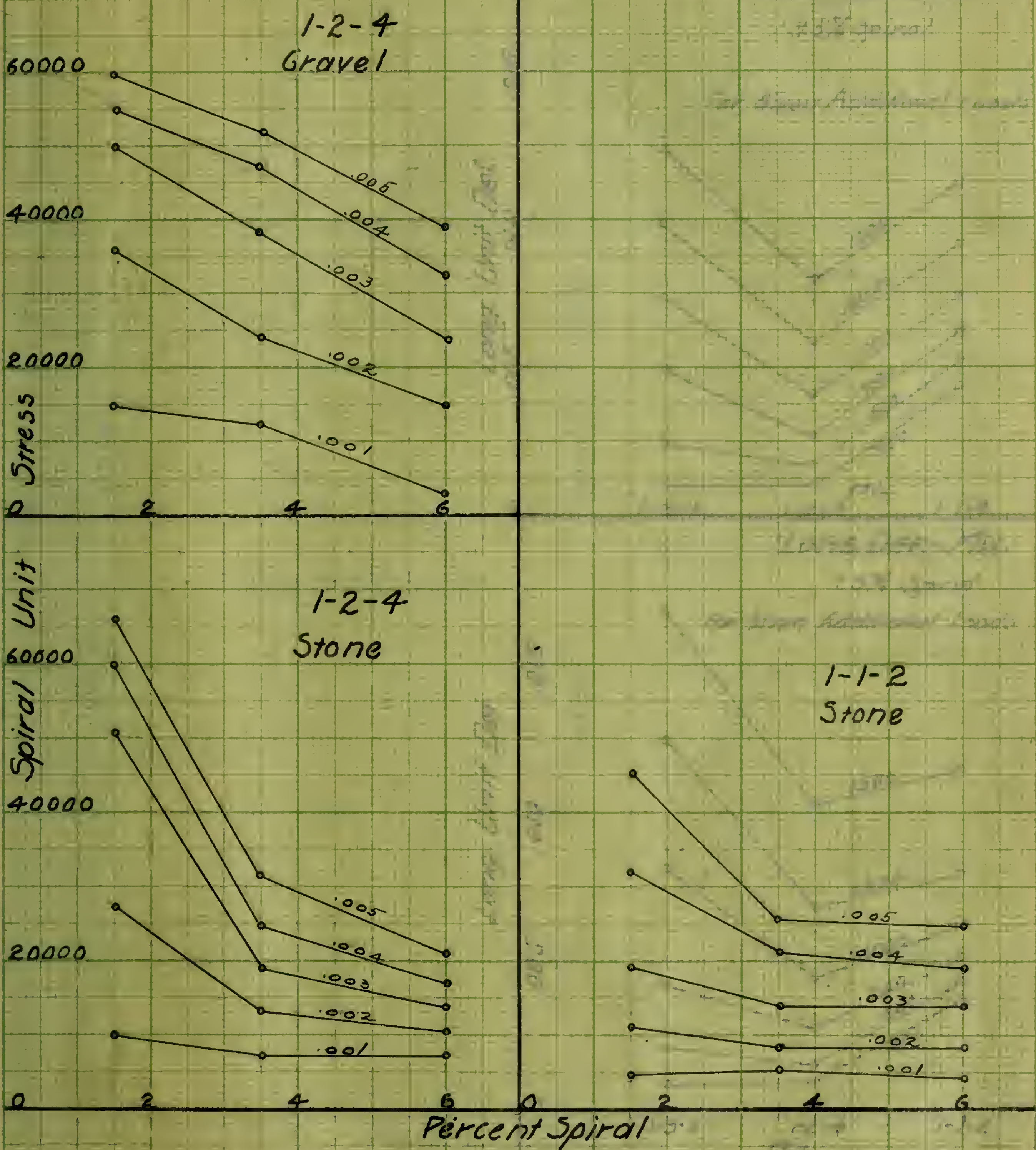
FOR VARIOUS ADD'N'L LDS.



UNIT STRESS - PERCENT

Av. CURVES

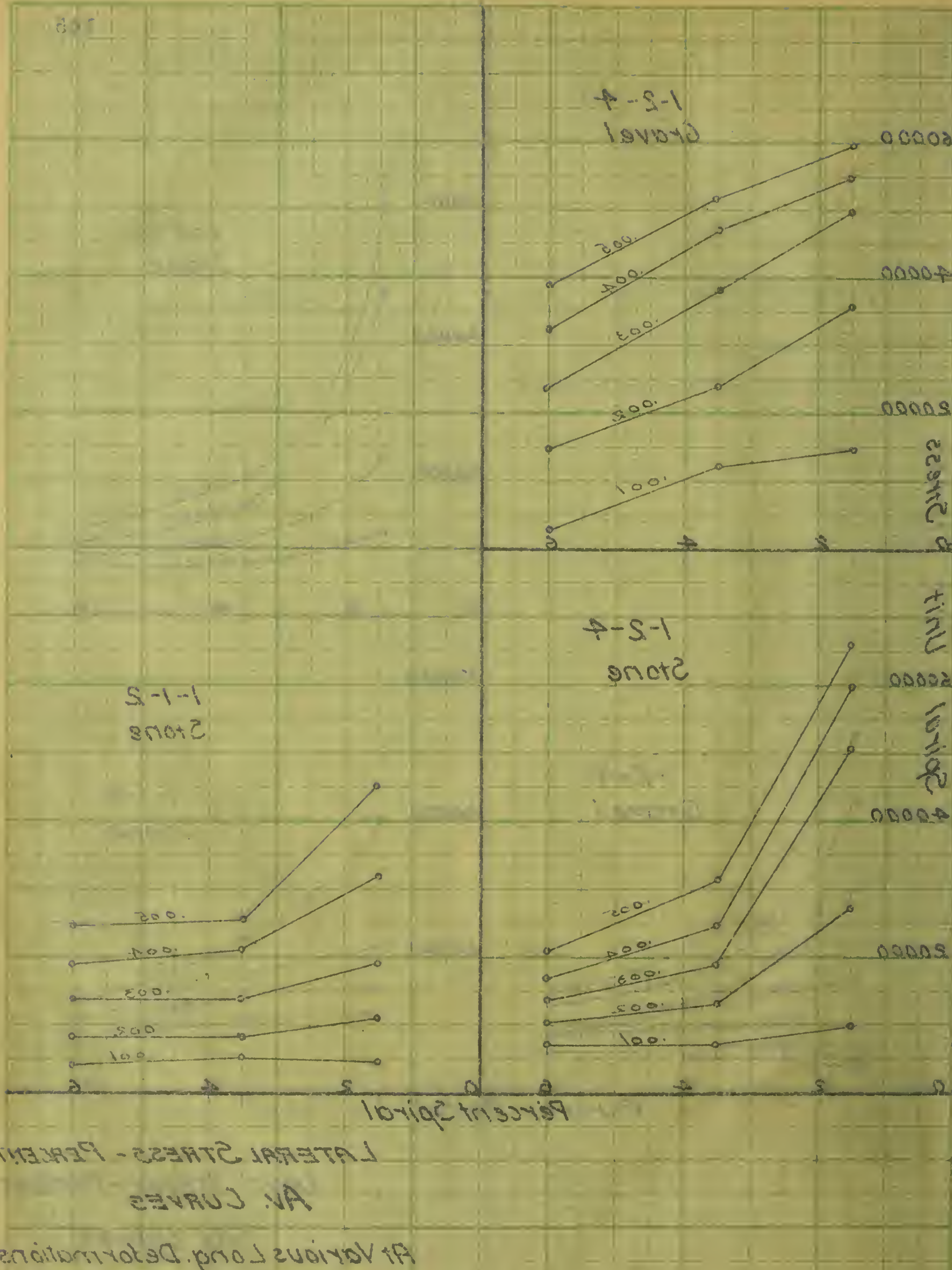
For Various Radii ds.

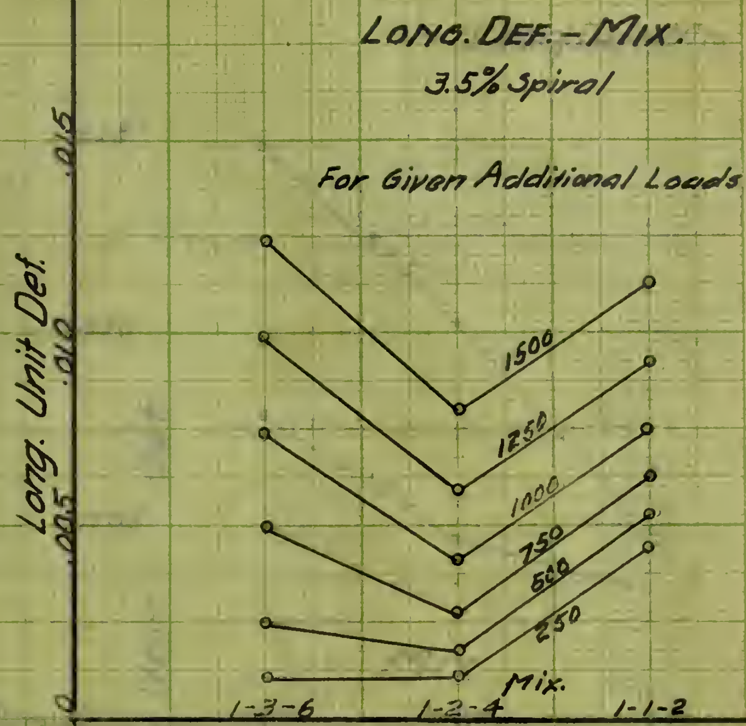


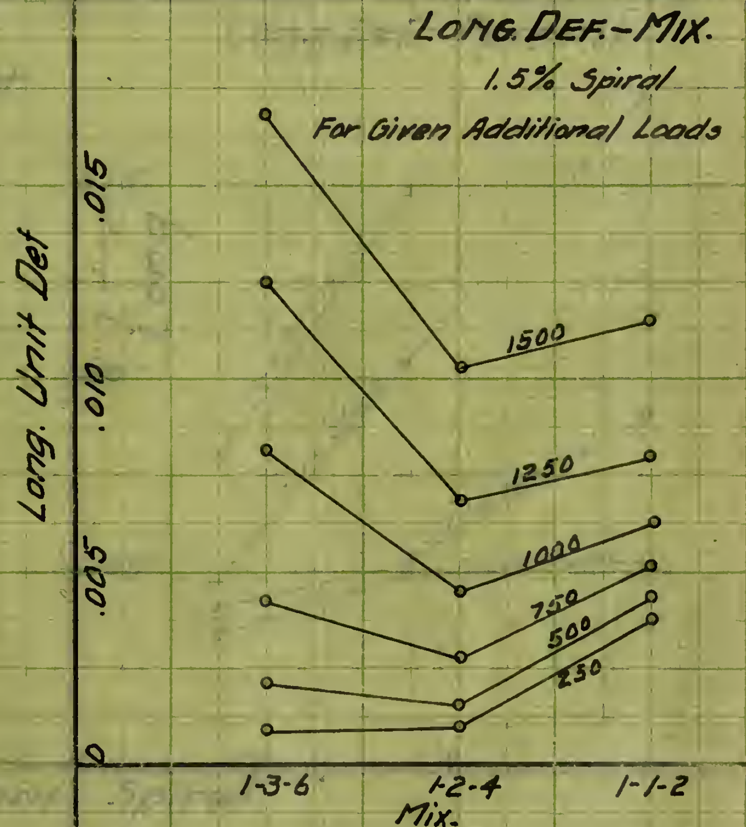
LATERAL STRESS - PERCENT

AV. CURVES

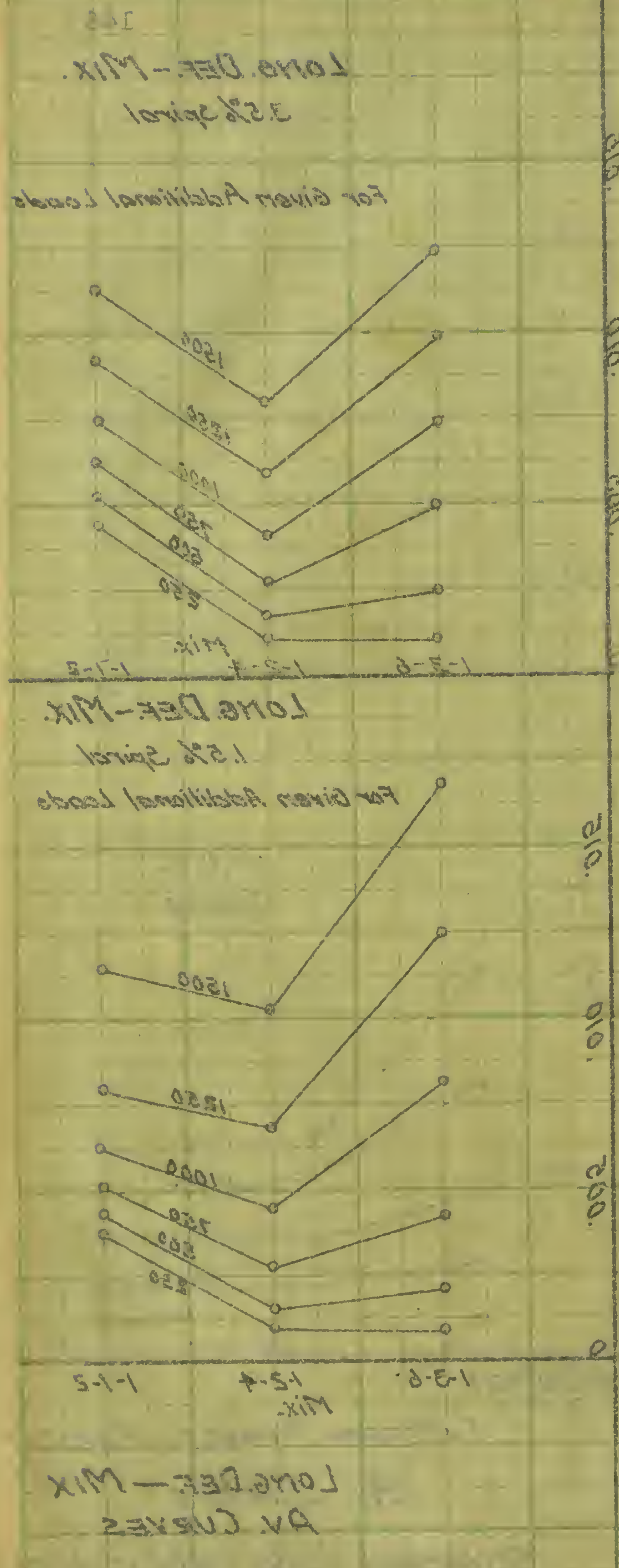
At Various Long. Deformations


1-2-4
Gravel
1-2-4
Stone
1-1-2
Stone
Unit Spiral Stress
60000
40000
20000
.005
.004
.003
.002
.001
Percent Spiral
LATERAL STRESS - PERCENT
Av. CURVES
At Various Long. Deformations

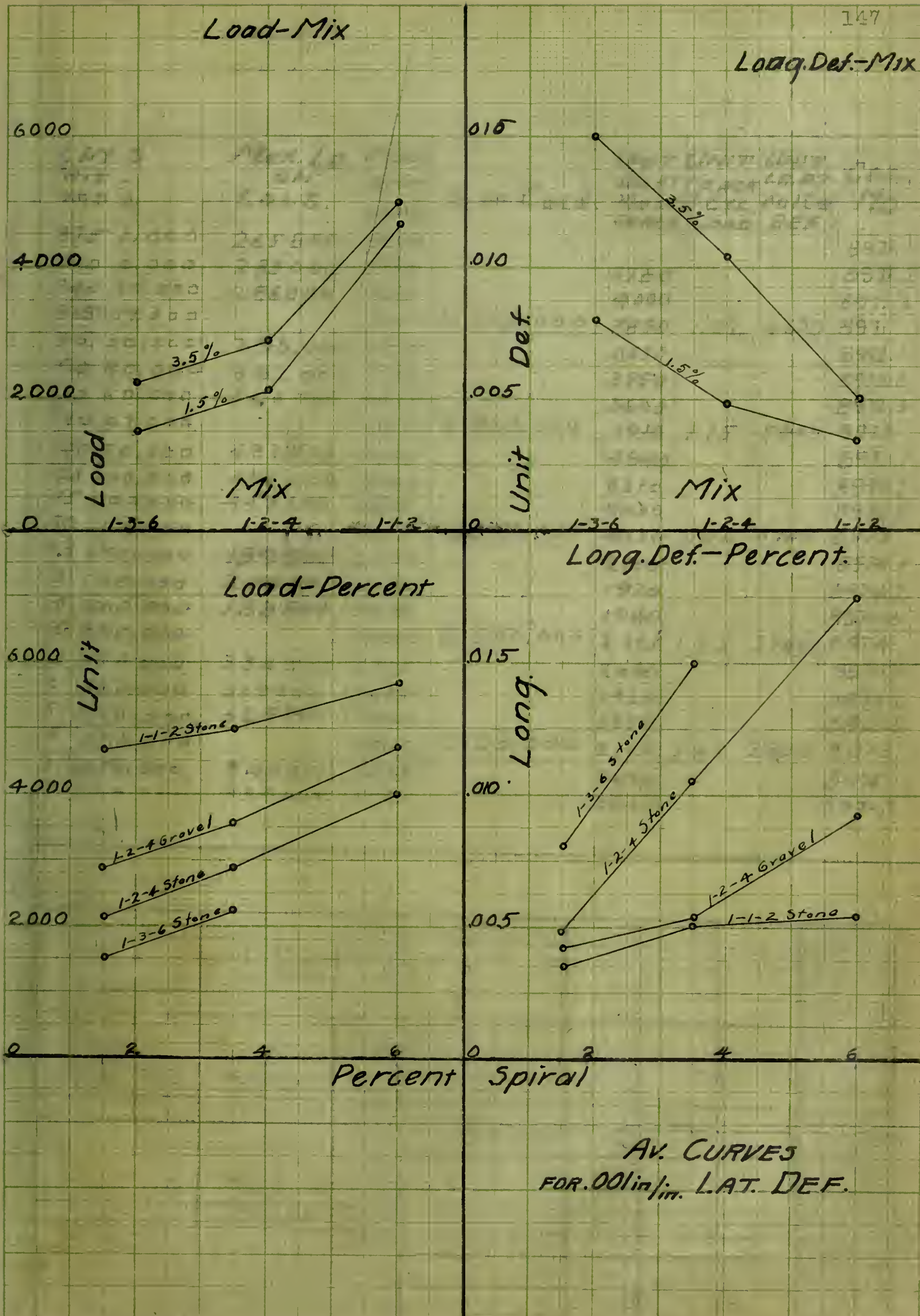


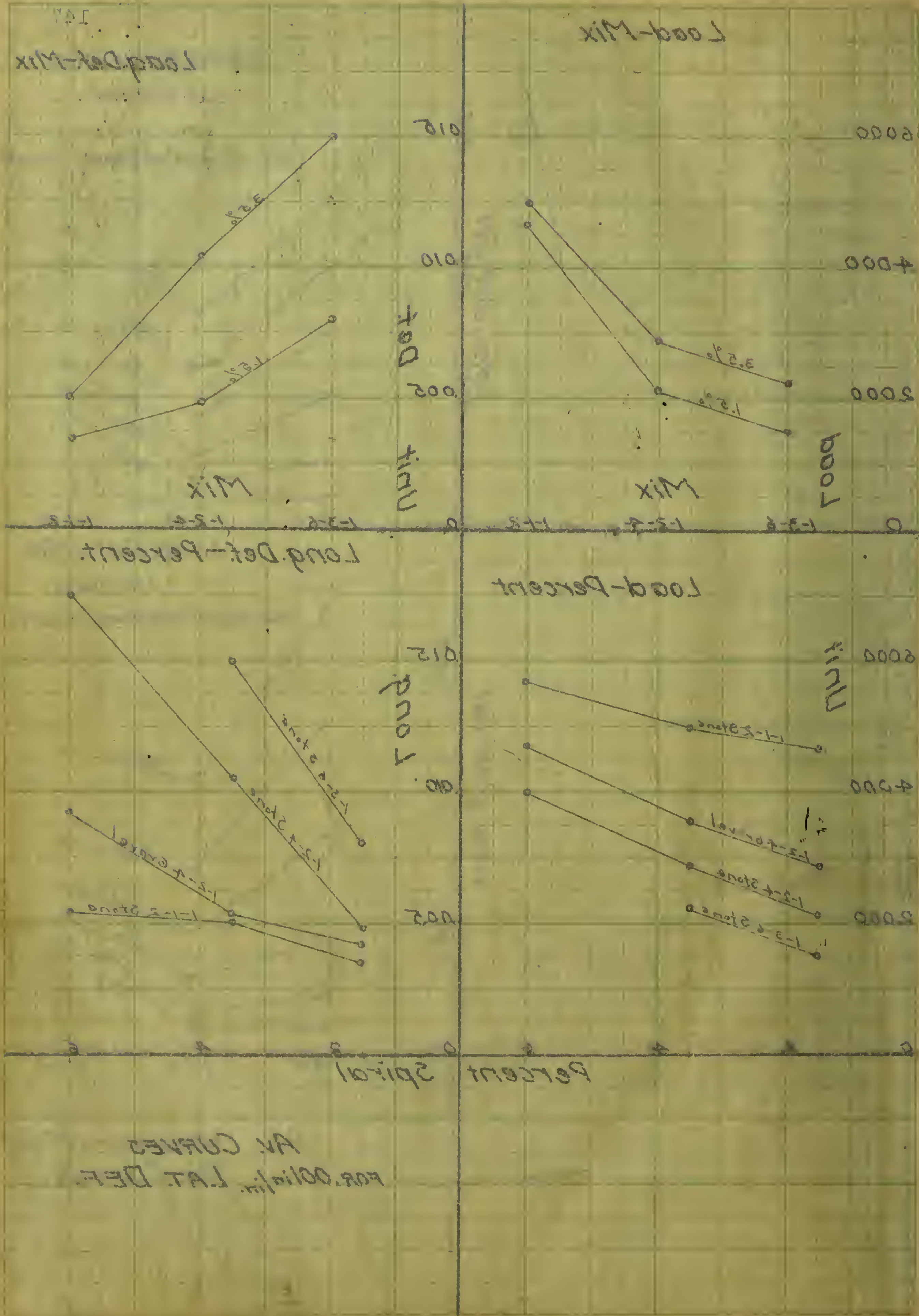


LONG. DEF. — MIX
AV. CURVES



Long. Def.-Mix.
3.5% Spiral
For Given Additional Loads
Long. Unit Def.
1500
1250
1000
750
500
250
1-1-2
1-2-4
1-3-6
Mix
Long. Def.-Mix.
1.5% Spiral
For Given Additional Loads
Long. Unit Def.
.015
.010
.005
0
Long. Def.—Mix
Av. Curves


Load-Mix
6000
4000
2000
0
3.5%
1.5%
Load
Mix
1-3-6
1-2-4
1-1-2
Long. Def.-Mix
.015
.010
.005
0
3.5%
1.5%
Unit
Def.
Mix
Load-Percent
Unit
6000
4000
2000
1-1-2 Stone
1-2-4 Gravel
1-2-4 Stone
1-3-6 Stone
2
4
6
Long. Def.-Percent.
Long.
.015
.010
.005
1-3-6 Stone
1-2-4 Stone
1-2-4 Gravel
1-1-2 Stone
Percent
Spiral
Av. CURVES
FOR .001 in/in. LAT. DEF.

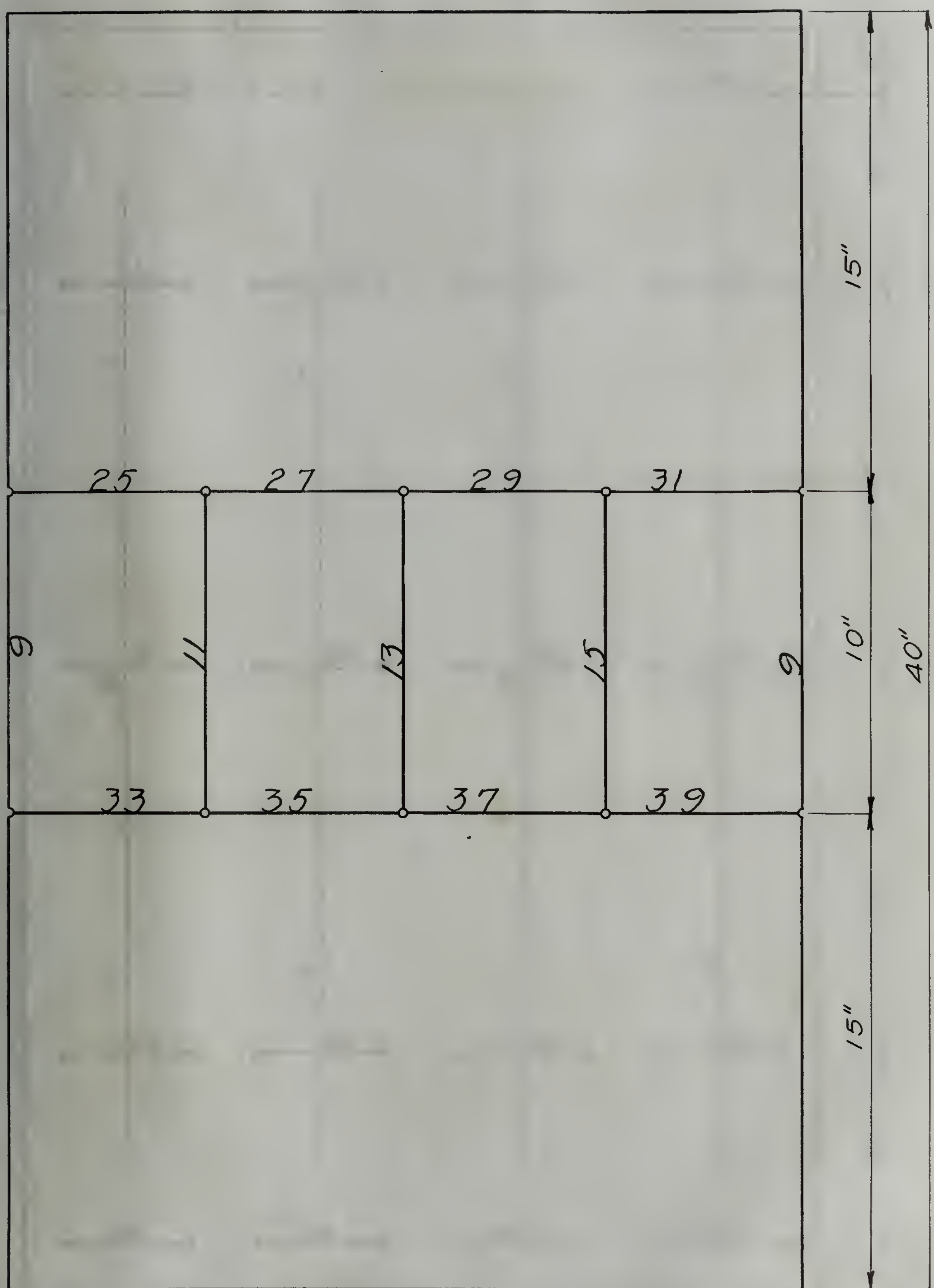


AV. CURVES
FOR .001 in/in. LAT. DEF.

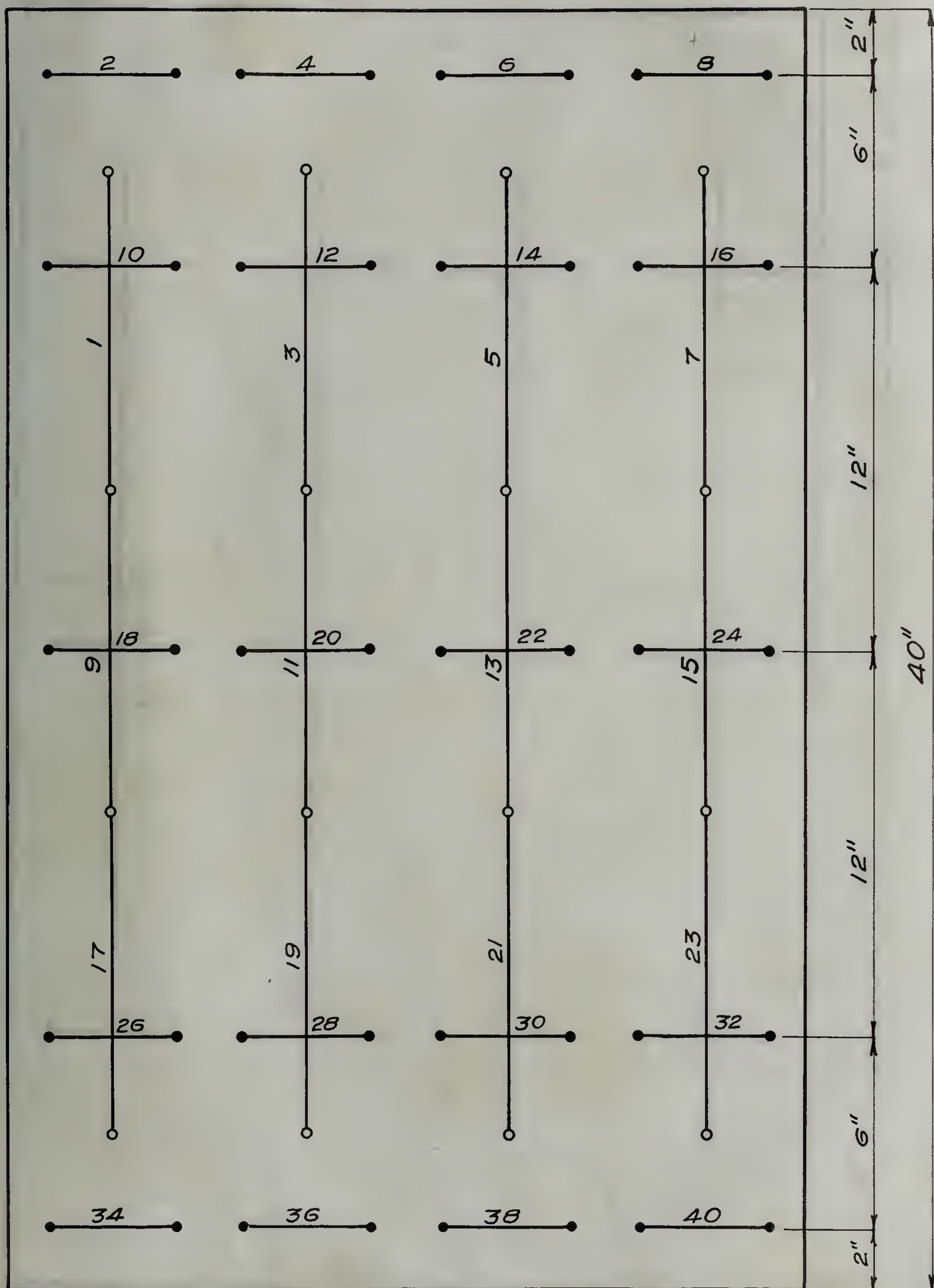
LIN:S UNIT = LOAD ÷ C	MAX. LD. ON COLS.	MAX UNIT LOAD	E_c OF COLS.	UNIT LD. AT FIRST CRACK	UNIT CRACK ÷ CYL. LOAD	UNIT LD. AT .001 IN. DEF	COL. NO.
875 0,000	265800	4870					8971.1
530 10,000	285000	5140		3780			8971.2
740 90,000	286000	5160		4000			8971.3
315 37,000		5060	3,300,000	3890	1.02	4670	8971
75 00,000	393,000	6930		4570			8972.1
90 80,000	397,000	7000		3550			8972.2
60 60,000	366 700	6620		3600			8972.3
10 47,000		6850	2,800,000	3910	1.15	5000	8972
40 50,000	431500	8260		4940			8973.1
40 00,000	455000	8500		3310			8973.2
75 00,000	459600	8485		4430			8973.3
50 17,000		8415	4,200,000	4230	1.02	5700	8973
93 570,000	189800	3410		2150			8974.1
0 00,000	204400	3510		1970			8974.2
5 000,000	188500	3400		1980			8974.3
0 890,000		3440	2,500,000	2035	1.25	2140	8974
0 700,000	334500	6030		2090			8975.1
500,000	319000	5630		1920			8975.2
800,000	325700	5740		2350			8975.3
000,000		5800	1,700,000	2120	1.33	2900	8975
850,000	340500	6450		2430			8976.1
[illegible]	330000	6250		2640			8976.2

TABLE 7.

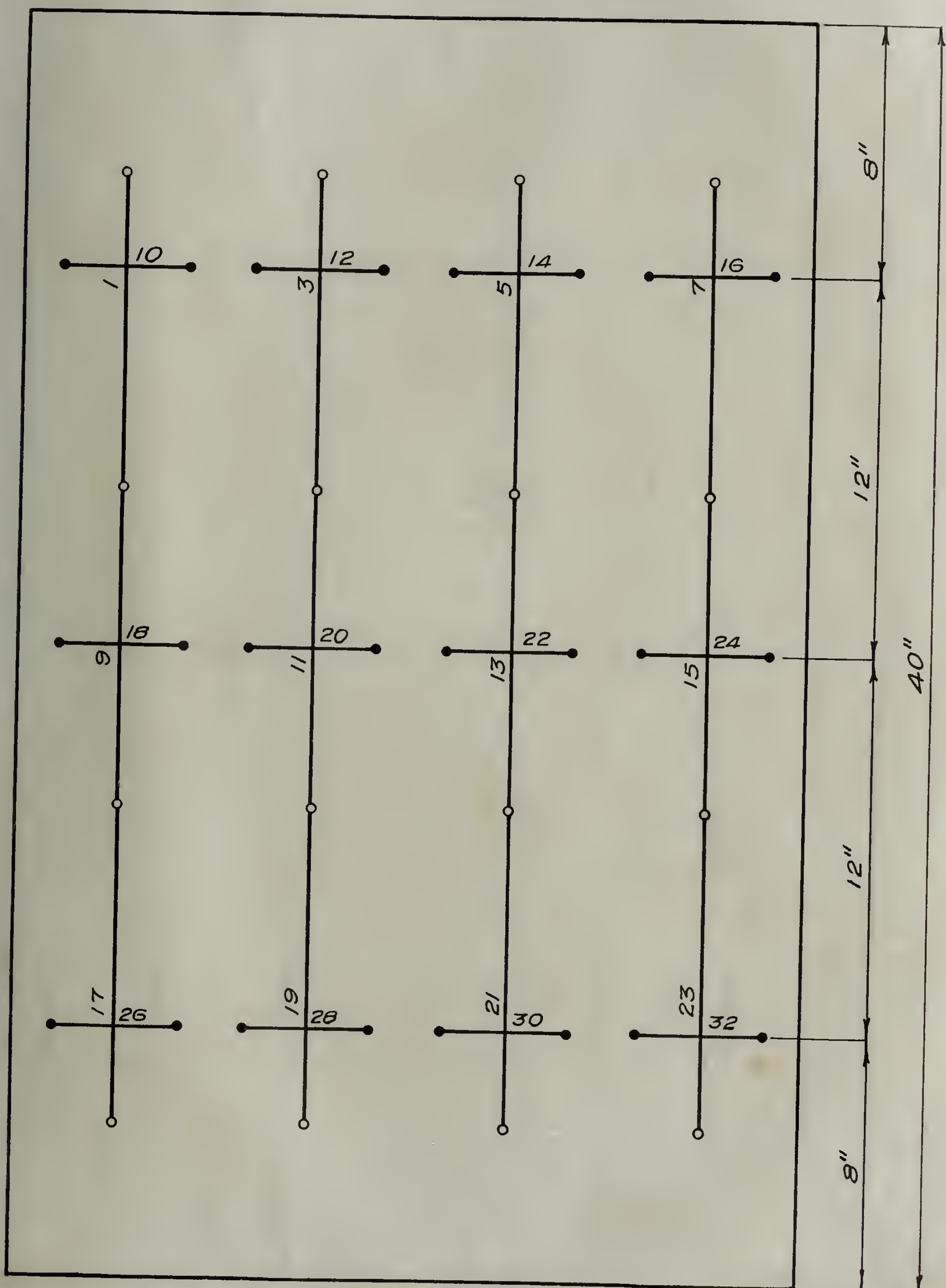
Col. No.	Weight of Cement (Pounds)	Sand	Stone	Water	Mix By Wt.	By Vol.	Perc't Water	O.TO.O. Spiral Diam. in.	Area sq. in.	Length in.	Spiral Diam in.	Pitch in.	Perc't	Date Made	Date Tested	Age Days	Cylinders Age	Unit Load	E_c	Max. Ld. on Cols.	Max Unit Load	E_c of Cols.	Unit Ld. at First Crack	Unit Crack ÷ Cyl. Load	Unit Ld. at .001 Lat. Def	Col. No.
8971.1	100	115	189	38.7	1-1.15-1.89	1-1-2 (Stone)	12.8	8.35	54.7	(40)	1/4	1.5	1.53	12-19-14	2-18-15	61	61	3875	3,120,000	265800	4870					8971.1
8971.2	"	"	"	40.0	"	"	13.1	8.40	55.5	40 1/8	"	"	1.50	12-29-14	2-27-15	60	59	3530	3,700,000	285000	5140		3780			8971.2
8971.3	"	"	"	40.0	"	"	13.1	8.40	55.5	40 1/8	"	"	1.50	1-6-15	3-8-15	61	63	4040	3,490,000	286000	5160		4000			8971.3
Av.	100	115	189	39.9	"								1.51			61	61	3815	3,437,000		5060	3,300,000	3890	1.02	4670	8971
8972.1	"	"	"	40.0	"	"	13.1	8.50	56.7	40 1/4	5/16	1.0	3.50	12-22-14	2-20-15	60	59	3775	3,800,000	393,000	6930		4570			8972.1
8972.2	"	"	"	40.0	"	"	13.1	8.40	56.7	40 1/4	"	"	3.49	12-31-14	3-1-15	60	64	3890	3,880,000	397,000	7000		3550			8972.2
8972.3	"	"	"	42.0	"	"	13.1	8.40	55.5	40 1/16	"	"	3.50	1-8-15	3-9-15	60	62	3560	3,260,000	366700	6620		3600			8972.3
Av.													3.50			60	62	3410	3,647,000		6850	2,800,000	3910	1.15	5000	8972
8973.1	"	"	"	42.0	"	"	13.3	8.15	52.2	40 1/4	1/2	1.5	5.97	12-24-15	2-23-15	61	62	4340	3,750,000	431500	8260		4940			8973.1
8973.2	"	"	"	40.0	"	"	13.1	8.25	53.5	40 1/4	"	"	5.94	1-2-15	3-3-15	60	61	4140	4,000,000	455000	8500		3310			8973.2
8973.3	"	"	"	40.0	"	"	13.1	8.30	54.2	40 1/4	"	"	5.94	1-12-15	3-13-15	60	60	3975	3,400,000	459600	8485		4430			8973.3
Av.													5.95			60	61	4150	3,717,000		8415	4,200,000	4230	1.02	5700	8973
8974.1	50	115	189	29.3	1-2.3-3.78	1-2-4 (Stone)	11.9	8.40	55.6	(40)	1/4	1.5	1.50	12-19-14	2-19-15	62	65	1803	2,570,000	189800	3410		2150			8974.1
8974.2	"	"	"	32.0	"	"	12.7	8.60	58.2	40 1/2	"	"	1.48	12-30-14	3-1-15	61	57	1510	3,100,000	204400	3510		1970			8974.2
8974.3	"	"	"	32.0	"	"	12.7	8.40	55.5	40 1/8	"	"	1.50	1-7-15	3-9-15	61	62	1545	3,000,000	188500	3400		1980			8974.3
Av.						"							1.49			61	61	1620	2,890,000		3440	2,500,000	2035	1.25	2140	8974
8975.1	"	"	"	31.9	"	"	12.7	8.40	55.5	(40)	5/16	1.0	3.52	12-23-14	2-22-15	61	61	1620	3,700,000	334500	6030		2090			8975.1
8975.2	"	"	"	32.0	"	"	12.7	8.50	56.7	40 1/4	"	"	3.49	1-1-15	3-2-15	60	59	1460	2,500,000	319000	5630		1920			8975.2
8975.3	"	"	"	32.0	"	"	12.7	8.50	56.7	40 1/4	"	"	3.49	1-11-15	3-12-15	60	60	1685	2,800,000	325700	5740		2350			8975.3
Av.													3.50			60	60	1585	3,000,000		5800	1,700,000	2120	1.33	2900	8975
8976.1	"	"	"	32.0	"	"	12.7	8.20	52.8	40 1/4	1/2	1.5	5.93	12-29-14	2-27-15	60	59	1690	3,850,000	340500	6450		2430			8976.1
8976.2	"	"	"	27.0	"	"	13.6	8.20	52.8	40 3/8	"	"	5.93	12-17-14	2-17-15	62	61	1695	3,230,000	330000	6250		2640			8976.2
8976.3	"	"	"	32.0	"	"	12.7	8.25	53.5	40 1/8	"	"	5.94	1-8-15	3-10-15	61	61	1650	3,400,000	382000	7140		2320			8976.3
Av.													5.93			61	60	1680	3,527,000		6610	1,900,000	2465	1.46	4000	8976
8977.1	35	121	199	32.5	1-3.46-5.7	1-3-6 (Stone)	13.0	8.30	54.2	40	1/4	1.5	1.53	12-21-14	2-19-15	60	60	765	2,510,000	172000	3180		1160			8977.1
8977.2	"	"	"	33.5	"	"	13.3	8.40	55.5	40	"	"	1.50	12-31-14	3-2-15	61	60	565	2,270,000	153600	2770		1115			8977.2
8977.3	"	"	"	33.5	"	"	13.3	8.45	56.2	40 1/4	"	"	1.49	1-9-15	3-11-15	61	62	645	2,100,000	168000	2990		1070			8977.3
Av.													1.51			61	61	660	2,290,000		2980	1,400,000	1115	1.69	1500	8977
8978.1	"	"	"	33.5	"	"	13.3	8.55	57.4	(40)	5/16	1.0	3.44	12-24-14	2-24-15	62	60	645	2,470,000	319500	5570		1390			8978.1
8978.2	"	"	"	33.5	"	"	13.3	8.50	56.7	40 1/8	"	"	3.49	1-4-15	3-5-15	60	60	670	2,380,000	291000	5140		1160			8978.2
8978.3	"	"	"	33.5	"	"	13.3	8.55	57.4	40 1/8	"	"	3.44	1-12-15	3-13-15	60	60	635	2,060,000	299000	5210		1360			8978.3
Av.													3.46			61	60	650	2,303,000		5310	1,000,000	1305	2.01	2250	8978
8979.1	50	115	210	28.0	1-2.3-4.2	1-2-4 (Gravel)	9.7	8.45	56.2	40 1/4	1/4	1.5	1.49	12-26-14	2-25-15	61	59	1785	3,460,000	221000	3930		2490			8979.1
8979.2	"	"	206	25.7	"	"	9.4	8.30	54.2	40 1/8	"	"	1.53	12-17-14	2-18-15	63	63	1810	2,740,000	213000	3930		2770			8979.2
8979.3	"	"	210	27.0			9.4	8.50	56.7	40 1/8	"	"	1.49	1-5-15	3-6-15	60	60	1930	3,750,000	214000	3780		2870			8979.3
Av.													1.50			61	61	1840	3,317,000		3880	2,400,000	2710	1.47	2900	8979
8980.1	"	"	"	27.0	"	"	9.4	8.45	56.2	40 1/4	5/16	1.0	3.45	12-23-14	2-23-15	62	61	1760	2,960,000	372600	6630		2780			8980.1
8980.2	"	"	"	27.0	"	"	9.4	8.75	60.2	40 1/8	"	"	3.40	1-2-15	3-4-15	61	60	1720	3,300,000	397500	6620		3370			8980.2
8980.3	"	"	"	27.0	"	"	9.4	8.45	56.2	40 1/8	"	"	3.45	1-11-15	3-3-15	61	70	1935	3,370,000	383000	6820		2770			8980.3
Av.													3.43			61	64	1805	3,210,000		6690	2,800,000	2975	1.65	3570	8980
8981.1	"	"	"	26.8	"	"	9.4	8.20	52.8	(40)	1/2	1.5	5.93	12-21-14	2-20-15	61	60	1670	3,300,000	424500	8060		3110			8981.1
8981.2	"	"	"	27.0	"	"	9.4	8.20	52.8	40 1/4	"	"	5.93	1-1-15	3-3-15	61	60	1720	3,470,000	464700	8820		2930			8981.2
8981.3	"	"	"	27.0	"	"	9.4	8.35	54.7	40 1/4	"	"	5.93	1-9-15	3-12-15	62	62	2100	3,520,000	456500	8340		2910			8981.3
Av.								PLAIN					5.93			61	61	1830	3,430,000		8410	2,800,000	2985	1.63	4720	8981
8982.1	100	115	189	40.0	1-1.15-1.89	1-1-2 Stone	13.1	(8.3)	54.2	39 3/4	NONE			12-28-14	2-26-15	60	60	3785	3,410,000	205000	3780		NONE			8982.1
8982.2	"	"	"	40.0	"	"	13.1	(8.3)	54.2	40 1/8				1-4-15	3-6-15	61	64	4080	3,610,000	210000	3880					8982.2
8982.3	"	"	"	40.0	"	"	13.1	(8.25)	53.5	40 3/8				1-13-15	3-16-15	62	59	3475	3,290,000	180000	3370					8982.3
Av.																61	61	3780	3,328,000		3680	3,300,000				8982
8983.1	50	115	189	32.0	1-2.3-3.78	1-2-4 Stone	12.7	(8.25)	53.5	40				12-26-14	2-25-15	61	59	1400	3,000,000	73700	1380					8983.1
8983.2	"	"	"	32.0	"	"	12.7	(8.3)	54.2	40 1/8				1-5-15	3-6-15	60	60	1350	3,650,000	62300	1150					8983.2
8983.3	"	"	"	32.0	"	"	12.7	(8.3)	54.2	40 1/8				1-15-15	3-16-15	60	60	1375		58000	1070					8983.3
Av.																60	60	1375	3,325,000		1200	3,000,000				8983
8984.1	35	121	199	33.5	1-3.46-5.7	1-3-6 Stone	13.3	(8.25)	53.5	40				12-22-14	2-20-15	60	62	685	2,070,000	31000	580					8984.1
8984.2	"	"	"	"	"	"	13.3	(8.2)	52.8	40 3/8				12-30-14	2-27-15	59	59	595	1,840,000	26500	500					8984.2
8984.3	"	"	"	"	"	"	13.3	(8.3)	54.2	40 1/8				1-7-15	3-8-15	60	62	615	2,440,000	26000	480					8984.3
Av.																60	61	630	2,117,000		520	2,000,000				8984
8985.1	50	115	210	27.0	1-2.3-4.2	1-2-4 Gravel	9.4	(8.25)	53.5	40 1/4				12-28-14	2-27-15	61	60	1670	4,200,000	91300	1710					8985.1
8985.2	"	"	"	"	"	"	9.4	(8.25)	53.5	40				1-6-15	3-8-15	61	59	2050	2,330,000	109500	2050					8985.2
8985.3	"	"	"	"	"	"	9.4	(8.25)	53.5	40 1/8				1-13-15	3-16-15	62	59	1740	3,570,000	95300	1780					8985.3
Av.																61	59	1820	3,357,000		1850	2,780,000				8985



DEVELOPED SURFACE OF PLAIN COLUMN, SHOWING LOCATION OF GAGE LINES



DEVELOPED SURFACE OF COLUMN, SHOWING LOCATION OF GAGE LINES
FOR COLUMN 3 OF EACH GROUP



DEVELOPED SURFACE OF COLUMN, SHOWING LOCATION OF GAGE LINES FOR COLUMN 1 & 2 OF EACH GROUP

TABLE

DRAWINGS

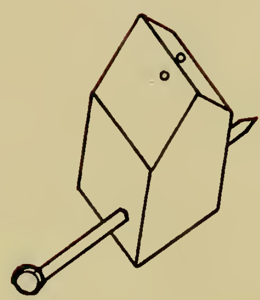


Illustration of steel plug used for gage points in the plain concrete columns. Note the nail used to anchor the plug in the concrete.

PHOTOGRAPHS

Showing condition at ultimate load of 1-1-2 stone concrete columns.

Showing condition at ultimate load of 1-2-4 stone concrete columns.

Showing manner of failure of 1-3-6 stone concrete columns. Also condition at ultimate load of three plain columns.

Showing the condition at ultimate load for the 1-2-4 gravel concrete columns.

Column 8976.3, showing the bend at the ultimate load.

Column 8981.3 showing the bent condition at the ultimate load.

Column 8982.2, showing manner of failure.